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UK Climate Projections: Briefing report

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Version 2, December 2010

Foreword from Professor Robert Watson, Chief Scientific Advisor, Defra

That the world's climate is changing is irrefutable. The Intergovernmental Panel on Climate Change stated in its most recent Assessment Report that it is very likely that the changes we have seen and measured are the result of anthropogenic emissions of greenhouse gases. While there may be some opportunities to be gained from a changing climate, we expect the bulk of the changes associated with a warming world to be negative for our society, economic sectors and the natural environment. And because of the time lag in the climate system, even with the most ambitious mitigation efforts, we are locked in to a further amount of climate change over the coming decades. Governments across the UK have an obligation to put in place measures to ensure that the negative effects of this are minimised for the UK, as well as taking advantage of any opportunities.

In order for us to plan effectively for a changing climate, it is essential that we utilise the best evidence we have available. This is the purpose of the UK Climate Projections; the result of seven years of work by the Met Office Hadley Centre, UK Climate Impacts Programme and a body of over thirty contributing organisations. For the first time, the Projections use a peer-reviewed, cutting edge methodology to give a measure of the uncertainty in the range of possible outcomes; a major advance beyond previous national scenarios. While the new set of Projections is designed to give much more information to users than previous climate scenarios, the information is necessarily more complex. Alongside this report to summarise the science behind the Projections, there are four accompanying scientific reports with more detail, as well as a dedicated website to access the climate information, supported by extensive user guidance and training.

I am delighted to offer this new state-of-the-art climate information, both to support decision makers who need to plan adaptation strategies, and as a major contribution towards international efforts to improve our ability to model future climate.

A handwritten signature in black ink that reads "R. T. Watson". The signature is written in a cursive, flowing style.

Contents



| | |
|--|----|
| Summary | 5 |
| 1 Introduction and purpose of this report | 9 |
| 2 How has the climate of the UK changed recently? | 11 |
| 3 Why new projections now? | 13 |
| 4 What climate change projections does UKCP09 provide? | 19 |
| 5 Some projections of changes in the UK climate | 28 |
| 6 Marine and coastal projections | 48 |

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Reviewers' comments have been extremely valuable in improving the final draft of this report. However, not all changes requested by all reviewers have been accepted by the authors, and the final report remains the responsibility of the authors.

The authors would like to thank the contributors and review groups to the four UKCP09 science reports on which this Briefing Report has been based.

The authors would like to acknowledge the original suggestion from Prof. Alan Thorpe, when Director of the Met Office Hadley Centre, for a project to quantify uncertainty using large climate model ensembles, without which the UKCP09 Probabilistic Projections would not have been possible.

Discussions with Prof. Jonathan Rougier, University of Bristol, have encouraged us to adopt the methodology for the UKCP09 probabilistic projections.

Summary

This report provides a summary of the 2009 UK Climate Projections (UKCP09), consolidating for the general reader the scientific reports describing the methodology and some key projections of future climate change for the UK over the 21st century. The UKCP09 Projections provide a basis for studies of impacts and vulnerability and decisions on adaptation to climate change in the UK over the 21st century. Projections are given of changes to climate, and of changes in the marine and coastal environment; recent trends in observed climate are also discussed. Each will be treated separately in this summary.

Observed trends in UK climate

- Central England Temperature has increased by about 1°C since the 1970s; it is likely that global emissions of man-made greenhouse gases have contributed significantly to this rise.
- Sea level around the UK has risen by about 1 mm/yr in the 20th century; the rate of rise in the 1990s and 2000s has been higher than this.

Projections of climate change

- Projections of climate change take into account uncertainty due to natural variability and our incomplete understanding of the climate system and its imperfect representation in models. The projections do this by giving the probabilities of a range of possible outcomes, as estimated by a specific methodology.
- Probability in UKCP09 can be seen as the relative degree to which each climate outcome is supported by current evidence, taking into account our understanding of climate science, observations and using expert judgement.
- Probabilistic projections are given at a resolution of 25 km over land, and as averages over administrative regions, river basins and marine regions, for seven overlapping 30-yr periods, and for three future emissions scenarios.
- There is a cascade of confidence in climate projections, with moderate confidence in those at continental scale; those at 25 km resolution are indicative to the extent that they reflect large-scale changes modified by local conditions such as mountains and coasts. The confidence in the climate change information also depends strongly on the variable under discussion.
- Errors in global climate model projections cannot be compensated by statistical procedures no matter how complex, and will be reflected in uncertainties at all scales.
- The methodology developed for UKCP09 to convert climate model simulations into probabilistic estimates of future change necessitates a number of expert choices and assumptions, with the result that the probabilities we specify are themselves uncertain. We do know that our probabilistic estimates are robust to reasonable variations within these assumptions.

Some examples of projected seasonal and annual changes

We summarise in the box below some changes by the 2080s with Medium emissions, but stress that projections can be very different for other time periods and other emissions scenarios. Users should look at the time period appropriate for their decisions, and examine projections for all three emissions scenarios, to gain a full appreciation of changes to which they might have to adapt.

Summer, winter and annual mean changes by the 2080s (relative to a 1961–1990 baseline) under the Medium emissions scenario. Central estimates of change (those at the 50% probability level) followed, in brackets, by changes which are very likely to be exceeded, and very likely not to be exceeded (10 and 90% probability levels, respectively).

- All areas of the UK warm, more so in summer than in winter. Changes in summer **mean temperatures** are greatest in parts of southern England (up to 4.2°C (2.2 to 6.8°C)) and least in the Scottish islands (just over 2.5°C (1.2 to 4.1°C)).

- **Mean daily maximum temperatures** increase everywhere. Increases in the summer average are up to 5.4°C (2.2 to 9.5°C) in parts of southern England and 2.8°C (1 to 5°C) in parts of northern Britain. Increases in winter are 1.5°C (0.7 to 2.7°C) to 2.5°C (1.3 to 4.4°C) across the country.
 - Changes in the **warmest day of summer** range from +2.4°C (–2.4 to +6.8°C) to +4.8°C (+0.2 to +12.3°C), depending on location, but with no simple geographical pattern.
 - **Mean daily minimum temperature** increases on average in winter by about 2.1°C (0.6 to 3.7°C) to 3.5°C (1.5 to 5.9°C) depending on location. In summer it increases by 2.7°C (1.3 to 4.5°C) to 4.1°C (2.0 to 7.1°C), with the biggest increases in southern Britain and the smallest in northern Scotland.
 - Central estimates of **annual precipitation** amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
 - The biggest changes in **precipitation in winter**, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
 - The biggest changes in **precipitation in summer**, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.
 - Changes in the **wettest day of the winter** range from zero (–12 to +13%) in parts of Scotland to +25% (+7 to +56%) in parts of England.
 - Changes in the **wettest day of the summer** range from –12% (–38 to +9%) in parts of southern England to +12% (–1 to +51%) in parts of Scotland.
 - **Relative humidity** decreases by around –9% (–20 to 0%) in summer in parts of southern England — by less elsewhere. In winter changes are a few percent or less everywhere.
 - **Summer-mean cloud amount** decreases, by up to –18% (–33 to –2%) in parts of southern UK (giving up to an extra +16 Wm^{–2} (–2 to +37 Wm^{–2}) of downward shortwave radiation) but increase by up to +5% (zero to +11%) in parts of northern Scotland. Changes in cloud amount are small (–10 to +10%) in winter.
- Projected changes in storms are very different in different climate models. Future changes in anticyclonic weather are equally unclear.
 - We have been unable to provide probabilistic projections of changes in snow. The Met Office Hadley Centre regional climate model projects reductions in winter mean snowfall of typically –65% to –80% over mountain areas and –80% to –95% elsewhere.
 - We make no assessment of how the urban heat island effect may change.
 - It is very unlikely that an abrupt change to the Atlantic Ocean Circulation (*Gulf Stream*) will occur this century.

Projected changes in daily climate

- UKCP09 provides synthetic daily time series of a number of climate variables from a weather generator, for the future 30-yr time periods, under the three emissions scenarios. These are given at 5 km resolution across the UK, the Isle of Man and the Channel Islands, but there is no climate change information additional to that at 25 km resolution.
- The Weather Generator is conditioned by change factors from the probabilistic projections; hence it must be used probabilistically by running at least 100 times.
- Analysis of results from the Weather Generator shows that increases in the number of days with high temperatures are found everywhere, particularly in southeast England, and reductions in the number of frost days are found, greatest where frost days are currently more frequent. Increases in the number of 10-day dry spells across the UK are found, more pronounced in southern England and Wales.

Projections of changes to the marine and coastal environment

- The range of absolute sea level rise around the UK (before land movements are included) is projected to be between 12 and 76 cm for the period 1990–2095 for the Medium emissions scenario.
- Taking vertical land movement into account gives slightly larger sea level rise projections relative to the land in the more southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. The land movements are typically between –10 and +10 cm over a century.
- Future projected trends in storm surge height are small everywhere around the UK, and in many places can be accounted for by natural variability. Consequently, changes in extreme sea level by 2100 will likely be dominated by increases in local mean sea level.
- Seasonal mean and extreme waves are generally projected to increase to the South West of the UK, reduce to the north of the UK and experience little change in the southern North Sea. Changes in the annual maxima are typically in the range –1.5 to +1 m.
- The shelf seas around the UK are projected to be 1.5 to 4°C warmer and ~0.2 practical salinity units (p.s.u.) fresher (lower salinity) by the end of the 21st century. The strength and period of summer stratification is projected to increase in the future.
- A wider range (known as H++) has also been developed for sea level rise and storm surges to be used for contingency planning and sensitivity analysis. The top of this range is considered very unlikely to be realised during the 21st century.

As our understanding, and our modelling and statistical capabilities, improve, it is very likely that projections will change in the future. The UKCP09 Projections are appropriate for decisions on adaptation to long-term climate change which need to be taken on the basis of current knowledge.

1 Introduction and purpose of this report

Climate is changing, both globally and in the UK. The Fourth Assessment Report (AR4) from the IPCC (Intergovernmental Panel on Climate Change) in 2007 said that “it is very likely that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century”, and more recent research has increased confidence in this statement. Changes projected by climate models are likely to result in significant impacts on the UK. And, because of the inertia of the climate system, current global emissions, and those over the past few decades, have already committed us to future climate change which cannot now, in any practical sense, be avoided.

These three factors: the high likelihood that mankind has already begun to change the earth’s climate, the projections of significant impacts in the future, and the commitment to further change over the next few decades irrespective of any emission reductions in the short term, argue very strongly for a strategy of adaptation to minimise the consequences, and maximise the opportunities, of climate change. To adapt effectively, planners and decision-makers need as much good information as possible on how climate will evolve, and supplying this is the aim of the new projections of UK climate change in the 21st century, known as UKCP09. They are one part of a UK government programme of work to put in place a new statutory framework on, and provide practical support for, adaptation.

The projections have been designed as input to the difficult choices that planners and other decision-makers will need to make, in sectors such as transport, healthcare, water resources and coastal defences, to ensure the UK is adapting well to the changes in climate that have already begun and are likely to grow in future. The underlying projections are in the form of numerical data that can be explored and downloaded with a purpose-built User Interface; this can also be used to visualise the data in the form of maps and graphs.

The UKCP09 Projections are supported by several publications, primarily online, in particular:

- The climate of the United Kingdom and recent trends
- UK Climate Projections science report: Climate change projections
- UK Climate Projections science report: Marine and coastal projections
- UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator

This report, and the science reports on which it is based, have been reviewed by the project Steering Group and User Panel. Reviewers' comments have been taken into account in improving the report. The methodologies used to generate the UKCP09 Projections were reviewed by an international panel of experts.

This Briefing Report aims to summarise the information in the four reports, for those requiring a general awareness of UK climate change. It begins by summarising recent observed changes in UK climate, in Section 2. It next turns to projections of change, where a major improvement in UKCP09 is the way in which uncertainty is dealt with. Because this is done differently for climate variables (temperature, rainfall, etc.) than it is for those in the marine and coastal environment (e.g. sea level and waves) the Briefing Report also follows this separation. Thus Section 3 summarises the methodology used to quantify uncertainties in climate variables, Section 4 describes the information provided in the probabilistic projections, and Section 5 shows some example projections of changes in temperature and precipitation. Section 6 presents the same sort of summary for the marine and coastal environment.

Figure 1 summarises all the information, in different forms, available to support the projections. The process of developing UKCP09 has included consultation with both climate experts and potential users, through its Steering Group and Users' Panel. Hence, the projections are designed to be aligned as closely as is possible with what users need to support their assessments of risk and choice of adaptation measures.

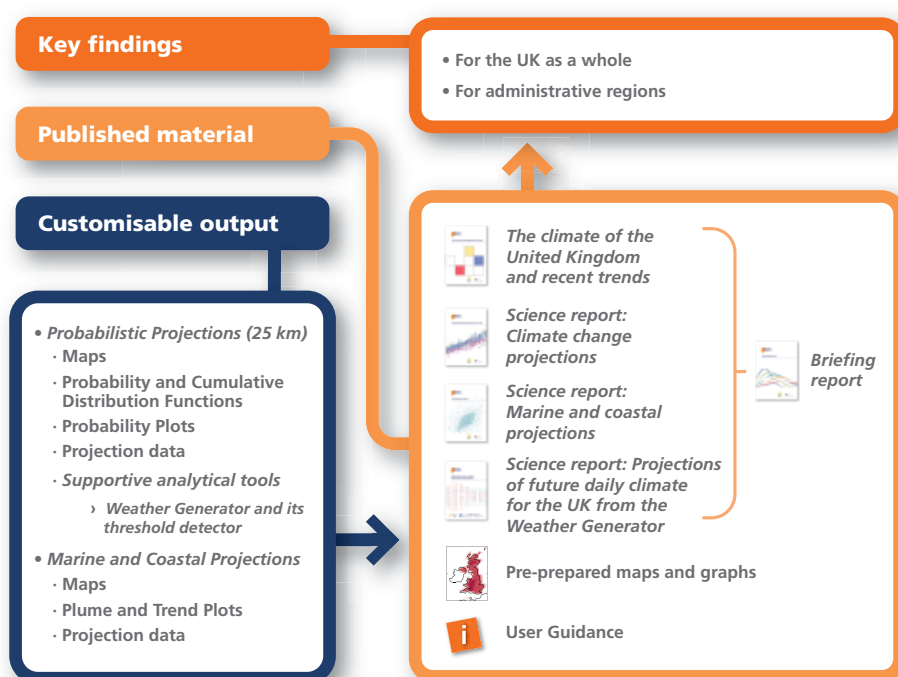


Figure 1: Information and publications supporting the UKCP09 projections. (Source: UKCIP.)
The products described under *Customisable Output* are explained later in this report.

2 How has the climate of the UK changed recently?

The climate of the UK is well monitored, and has been for some time, enabling trends to be identified where they exist. We discuss these below, for temperature in some detail and then for other climate variables.

Temperature

Central England Temperature (CET), the average of three observing stations in Hertfordshire, Worcestershire and Lancashire, has been monitored instrumentally since 1772, and long term changes in it are representative of those across most of the UK. Figure 2 shows that, after a period of relative stability for most of the 20th century, CET has increased by about a degree Celsius since the 1970s. Studies have shown that this observed rate of warming cannot be explained by natural climate variations, but is consistent with the response to increasing greenhouse gases and aerosols simulated by the Met Office Hadley Centre climate model. It is likely, therefore, that global man-made emissions of greenhouse gases have played a significant role in the recent warming of the UK. However, CET has risen faster in the last few decades than the global mean temperature over land, and this may be partly due to the influence of higher North Atlantic sea-surface temperatures, arising from natural variations in the North Atlantic circulation.

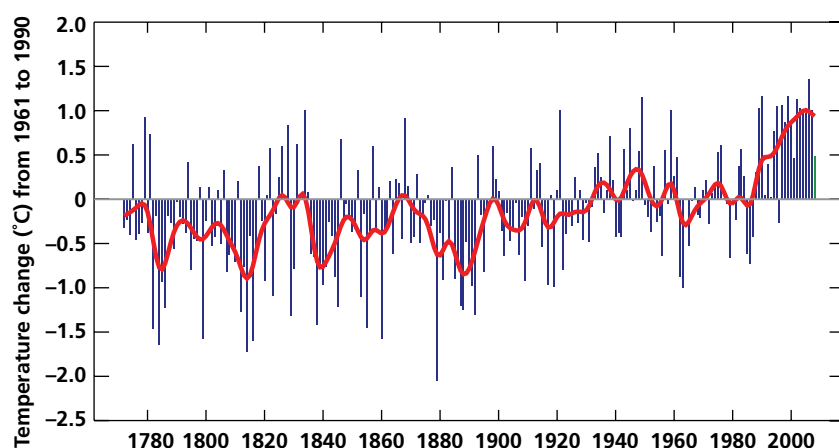


Figure 2: Changes in CET annual values (blue bars) from 1772 to 2008, relative to the average over the 1961–1990 baseline period (about 9.5°C). The green bar is that for 2008. Decadal variations in temperature are shown in red. (Source: Met Office Hadley Centre.)

Temperatures in Wales, Scotland and Northern Ireland have risen by about 0.7–0.8°C since about 1980, and sea surface temperatures around the UK coast have risen over the past three decades by about 0.7°C. However, because the length of data in each case is relatively short, research to date has not attributed these changes to specific causes.

Other variables

Other aspects of UK climate have also changed. Annual mean precipitation over England and Wales has not changed significantly since records began in 1766. Seasonal-mean precipitation is highly variable, but appears to have decreased in summer and increased in winter, although with little change in the latter over the last 50 yr. There have also been changes to the proportion of winter rainfall coming from heavy precipitation events: in winter all regions of the UK have experienced an increase over the past 45 yr; in summer all regions except NE England and N Scotland have experienced decreases. Severe windstorms have become more frequent in the past few decades, though not above a level seen in the 1920s (see Figure 3). Sea level around the UK rose by about 1 mm/yr in the 20th century, corrected for land movement. The rate of rise in the 1990s and 2000s has been higher than this.

More information on recent changes is given in the UKCP09 report *The climate of the United Kingdom and recent trends*.

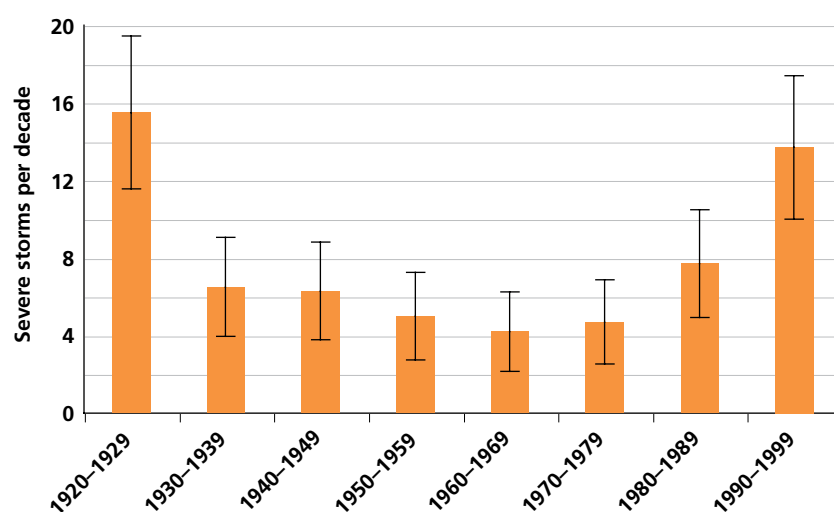


Figure 3: The total number of severe storms per decade over the UK and Ireland during the half-year period October to March, from the 1920s to the 1990s. Error bars show a measure of the uncertainty in the number for each decade. (Source: Met Office Hadley Centre.)

3 Why new projections now?

Scenarios of UK climate change were published by UKCIP in 1998 and 2002, and many assessments of impacts and vulnerability, and guidance for adaptation, have been based on them. Recent research has shown that most recent trends in observed climate fall broadly within the range of projections shown in these scenarios. Continuing improvements in our understanding of the climate system and in modelling allows us to periodically update projections, which also helps to meet increasingly sophisticated user requirements. One example of our better understanding is the growing recognition of how changes in the carbon cycle can act to exacerbate climate change; this factor is included in UKCP09 for the first time. A further example of scientific improvements concerns uncertainties; reports accompanying previous UKCIP scenarios have mentioned the lack of a credible approach to dealing with uncertainties.

The development of new techniques, together with increased computing power enabling them to be exploited, has allowed us to quantify the spread of future projections consistent with major known sources of uncertainty. As mentioned earlier, this is done in different ways for projections of changes in climate and for changes in the marine environment; for the remainder of this section we consider changes in climate. Uncertainty in this case is dealt with by presenting projections which are probabilistic in nature. This sort of presentation is more informative than the single projection (for a given emissions scenario) in UKCIP02, or even a range of different projections from different climate models (as in Figure 4), but is also necessarily more complex. It gives the user the relative probability of different outcomes, based on the strength of evidence, and more openly reflects the state of the science. This is why probabilistic projections were adopted by IPCC for the first time in their most recent science assessment. The UKCP09 Projections respond to demands from a wide range of users for this level of detail.

What are the main uncertainties; how do we include them in UKCP09 Projections?

Uncertainty in climate change projections is a major problem for those planning to adapt to a changing climate. Adapting to a smaller change (or one in the wrong direction) than that which actually occurs could result in costly impacts and endanger lives, yet adapting to too large a change (or, again, one in the wrong direction), could waste money. Uncertainty in projections of future climate change arises from three causes:

- Natural climate variability;
- Incomplete understanding of Earth system processes and their imperfect representation in climate models (which we term *modelling uncertainty*); and
- Uncertainty in future man-made emissions (of greenhouse gases and other pollutants).

These causes are considered in turn below.

- **Natural variability.** There are two types of natural climate variability. The first arises from natural external influences on climate — changes in the amount of particles in the atmosphere from volcanoes, or changes in the energy we receive from the sun. These have influenced climate in the past, although

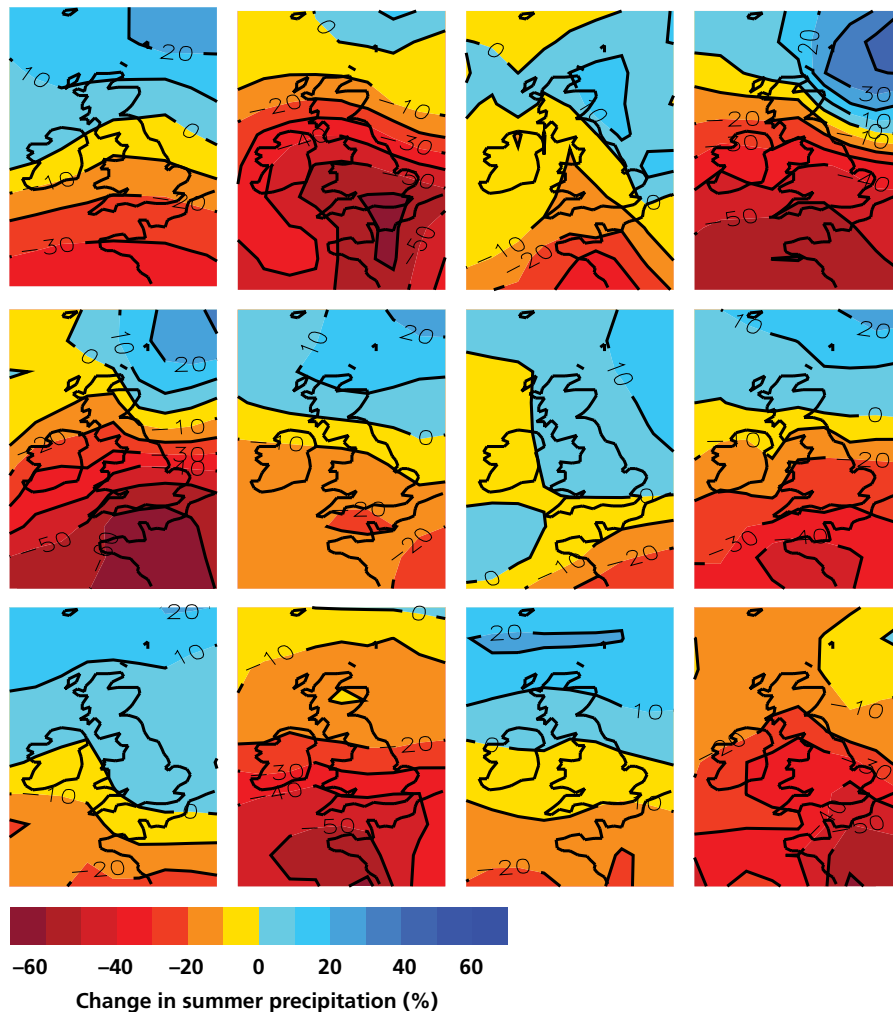


Figure 4: Changes (%) in summer (June–August) precipitation by the period 2071–2100 compared to 1961–1990, from 12 climate models, each of which took part in the IPCC AR4, all driven with the same emissions scenario. (Data source: PCMDI for IPCC.)

over the last 50 yr their effect has been much smaller than that due to man's activities. Because we have no way of predicting future changes to the sun or volcanic activity, their climate effects cannot be included in UKCP09 projections. The second type of long-term natural variability is due to internal processes in the climate system, typically driven by interactions between ocean and atmosphere, such as El Niño. There are encouraging signs that some aspects of natural internal variability over the next decade or two can be predicted, but this has only been shown so far for global temperature. Nevertheless, we can estimate the uncertainty in projections from this cause, and this is done in UKCP09.

- **Modelling uncertainty.** The effect of modelling uncertainty manifests itself in the different projections from different climate models, both globally and, to an even greater extent, at local or regional scales where information is critically needed. This is illustrated in Figure 4. Local-scale differences between projections from different models are no smaller now than those shown in UKCP02 7 yr ago, despite improvements to models. For this reason, we cannot assume that continuing model improvements will quickly lead to a reduction of uncertainties in projections.

Compared to previous UKCIP scenarios, for the first time we are able to estimate modelling uncertainty as a spread of outcomes (consistent with current understanding), expressed to the user as *probabilistic projections* of climate change for certain key climate variables (Figure 5). This provides information on the estimated relative likelihood of different future outcomes, in the form of a *probability density function* or PDF (see Box 3). The PDF takes into account both the known modelling uncertainty and that due to natural variability, but not the uncertainty due to future emissions.

How do we generate the probability distribution? The reason why different climate models give different projections is because they use different, but plausible, representations of climate processes. Hence, we generate probability distributions using projections from two *ensembles* of global model projections:

- » a large ensemble of variants of the Met Office Hadley Centre global model, each representing climate processes in the atmosphere and at the surface in a different way
- » an ensemble of 12 other international global models which allows us to sample the effects of modelling errors which cannot be incorporated in variants of the Met Office Hadley Centre model alone — obviously errors due to processes missing from all models cannot be sampled by any technique.

Using alternative climate models also fulfils one of the main user requests identified from UKCIP consultations and reviews, that the projections should not be based solely on the Met Office Hadley Centre model. To do this, we have had to develop a methodology to incorporate a number of single projections from alternative global models into a far larger number of variants of the Met Office Hadley Centre global model. We then use further model ensembles to include uncertainties in additional Earth system processes, including the cooling effect of sulphate aerosol, ocean processes and in feedbacks from the land carbon cycle. Finally the uncertainties in scaling projections through the whole of the 21st century, and at a resolution of 25 km, are also added. Of

Box 1: The carbon, sulphur and methane cycles: what is and isn't included

The carbon cycle

Currently about half of the emissions of CO₂ from human activities (fossil fuel combustion and land use change) are taken up by sinks on land (vegetation and soils) and in the ocean (seawater and ecosystems within it), leaving the remainder of the CO₂ in the atmosphere where it increases concentrations there. But as climate starts to change, carbon sinks can also change, so may be able to absorb more, or less, CO₂ from the atmosphere. For example, as soils warm they increase their respiration of CO₂ back to the atmosphere and their ability to remove CO₂ will weaken, leading to atmospheric concentrations being higher than they would otherwise be. This is an example of a positive feedback, that is, one which acts to enhance the effect of initial man-made emissions. On the other hand, a warmer climate will encourage the growth of boreal forests which would take up more CO₂ from the atmosphere — a negative feedback (that is, one which acts to reduce atmospheric concentrations). There are a host of such feedbacks, both positive and negative; the net effect is uncertain, but is positive in all available models. In UKCP09 the feedback between climate and the carbon cycle is included in the probabilistic projections; the uncertainty in the feedback from the land carbon cycle is included, but not the smaller uncertainty in the feedback from the ocean carbon cycle.

Sulphate aerosol

Sulphur gases emitted from fossil fuel burning, and naturally from the oceans, forms small particles in the atmosphere — sulphate aerosol. This can have a substantial cooling effect on climate, both directly (by reflecting back some of the incoming solar radiation) and indirectly (by making clouds more reflective and by increasing their lifetime). The direct and first indirect effects, and their uncertainties, are included in the UKCP09 Projections.

Other climate factors and feedbacks

Changes in other agents, such as black carbon and sea-salt, are not included in UKCP09; their effect is estimated to be small relative to greenhouse gases and sulphate aerosols. Feedbacks from the methane cycle (e.g. increased emissions from wetlands and melting permafrost which could further warm climate), and the second indirect effect of sulphate aerosols (which would act to cool), are also not included in UKCP09; they may be significant but are not quantified sufficiently well to include with any confidence.

course, no methodology can sample uncertainties due to processes that are unknown, or so uncertain that we cannot yet include them in models, or due to shortcomings which are common to all models (see Box 1).

The progression to probabilistic projections based on model ensembles has meant that not all of the properties and characteristics of the UKCIP02 scenarios could be carried across to UKCIP09 — the direct provision of daily time series from climate model output, for example (but see *Changes in daily climate* on page 25). Thus the new projections are not a “drop in” replacement or straightforward update of UKCIP02 (see Table 2).

Figure 5: A schematic diagram showing the progression from UKCIP02 to UKCIP09, using temperature as an example. The single estimate of change in temperature from UKCIP02 (left, for a given emissions scenario, location, time period, etc.) gives no information about uncertainty. A range of changes in temperature from different climate models (centre) gives no information about which model to use, and only partly reflects uncertainties. The PDF given in UKCIP09 (right) shows the probability of different outcomes, that is, different amounts of change in temperature.

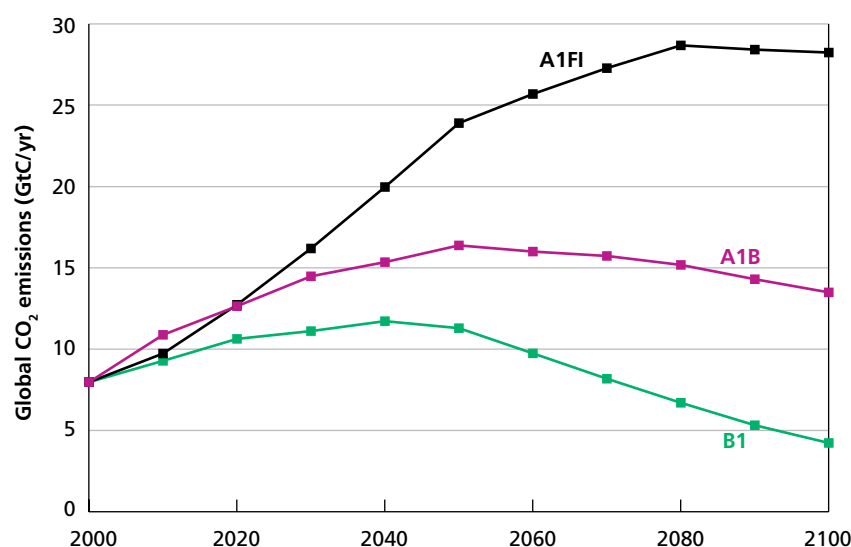
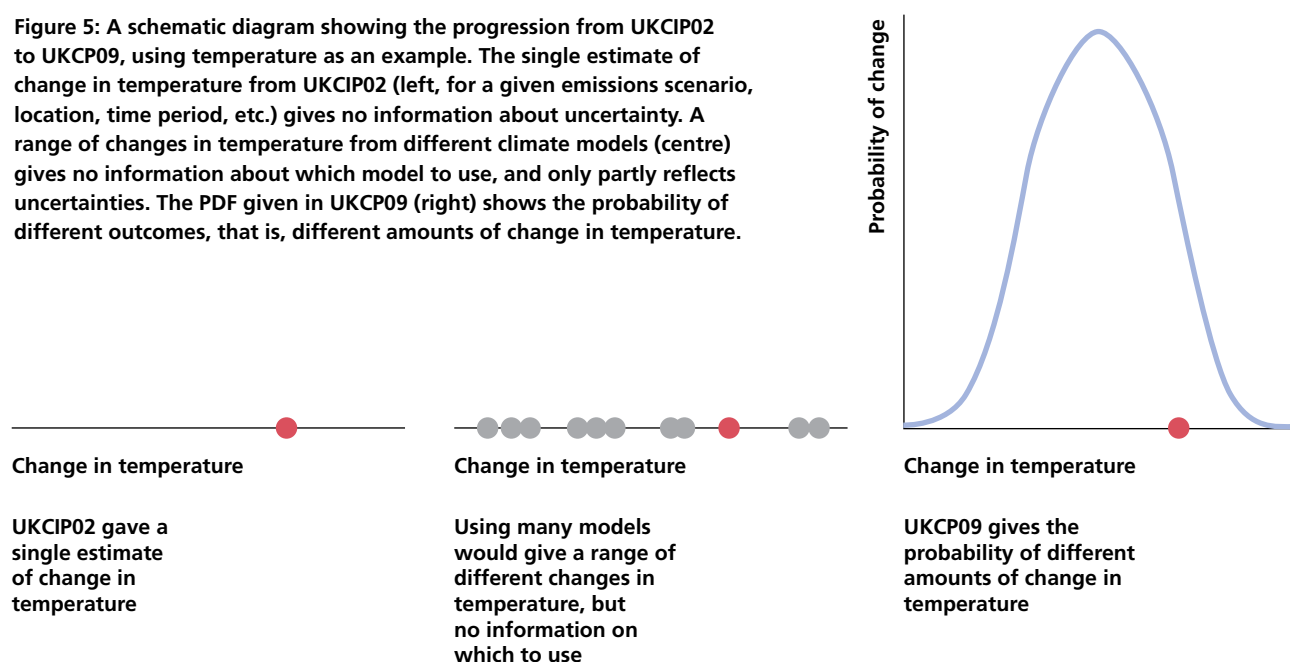


Figure 6: CO₂ emissions under the three IPCC SRES scenarios used in UKCIP09: A1FI (black: High emissions), A1B (purple: Medium emissions) and B1 (green: Low emissions). (Source: IPCC.)

- **Emissions uncertainty.** The description of UKCP09 probabilistic projections above does not discuss the effect of uncertainties in future emissions. The latter, though small over the next two or three decades mainly because of climate system inertia, will be substantial in the second half of the century. We therefore include the effect of emissions uncertainty by presenting separate probabilistic projections of future climate change for three scenarios of future emissions. These were decided, following consultation, as the A1FI, A1B and B1 scenarios in the IPCC Special Report on Emission Scenarios (SRES) — renamed for simplicity in UKCP09 as High, Medium and Low respectively. These scenarios include a wide range of greenhouse gases and other pollutants; as an example, the CO₂ emissions are shown in Figure 6. (Note that, because future emissions will be determined by human choices, relative likelihoods cannot be assigned to these scenarios, and we cannot combine emissions uncertainty and other uncertainties to produce a single probabilistic projection covering all types of uncertainty.) All scenarios are *non-interventionist*, that is they assume no political action to reduce emissions in order to mitigate climate change; differences between them arise purely from different assumptions about future socioeconomic developments. The online User Guidance, and Annex 1 of *UK Climate Projections science report: Climate change projections*, both give further details.

4 What climate change projections does UKCP09 provide?

Probabilistic projections

UKCP09 gives probabilistic projections for a number of atmospheric variables, with different temporal and spatial averaging, by several future time periods, under three future emissions scenarios.

The **variables** available over land, and over marine regions, are shown in Table 1. Precipitation is a total of precipitation of all types — rain, snow and hail — and is given as a rate, in millimetres per day; however, when discussing monthly, seasonal or annual average changes we refer to it for convenience as simply *precipitation*. Mean daily maximum (minimum) temperature is sometimes shortened to *maximum (minimum) temperature*, again for convenience.

In order to be statistically robust, the changes in extreme values (such as the 99th percentile of daily precipitation rate) are calculated from 30 yr of daily changes in a season. In Table 1 more user-friendly (albeit less accurate) names for these variables follow in brackets.

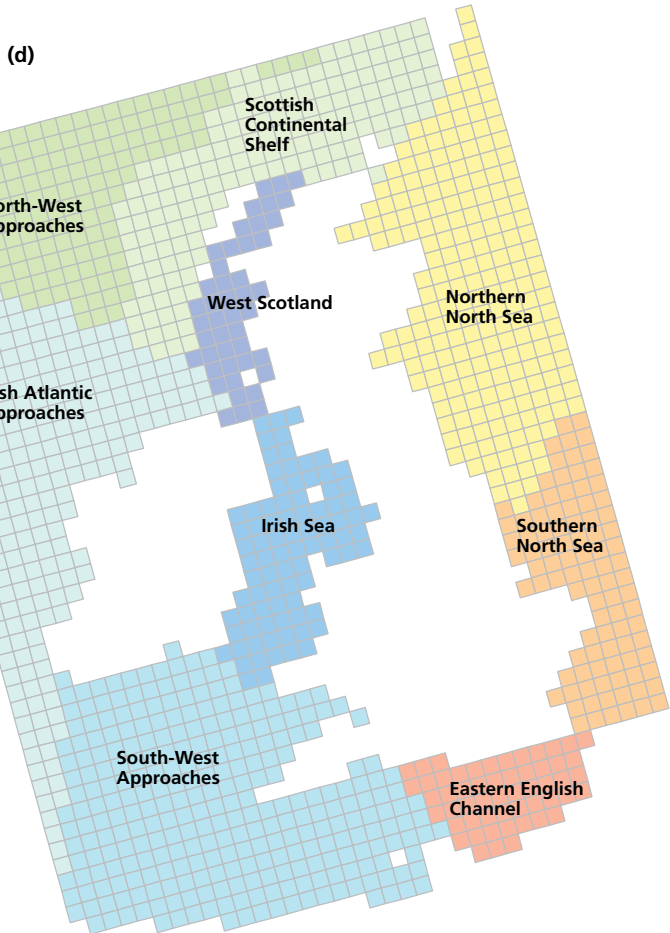
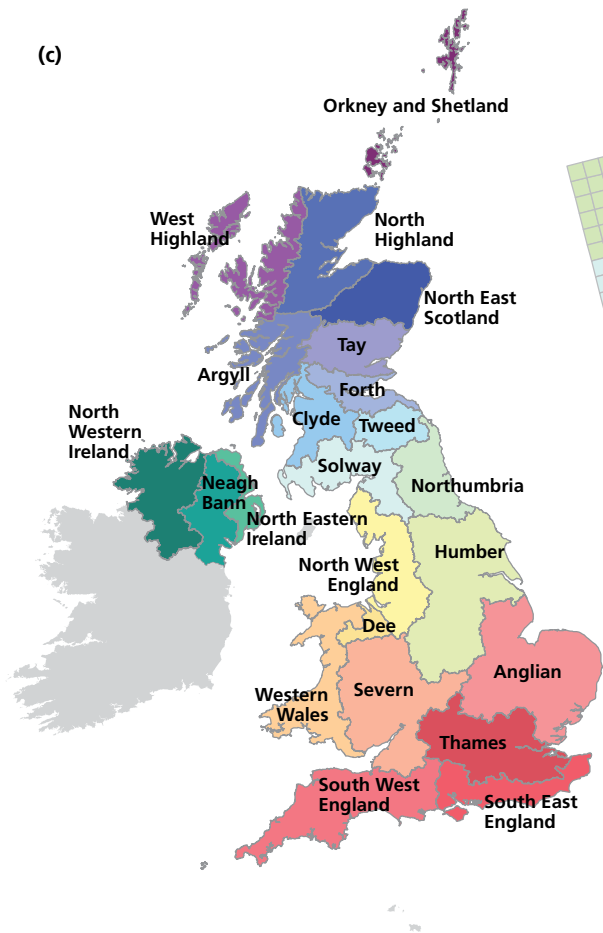
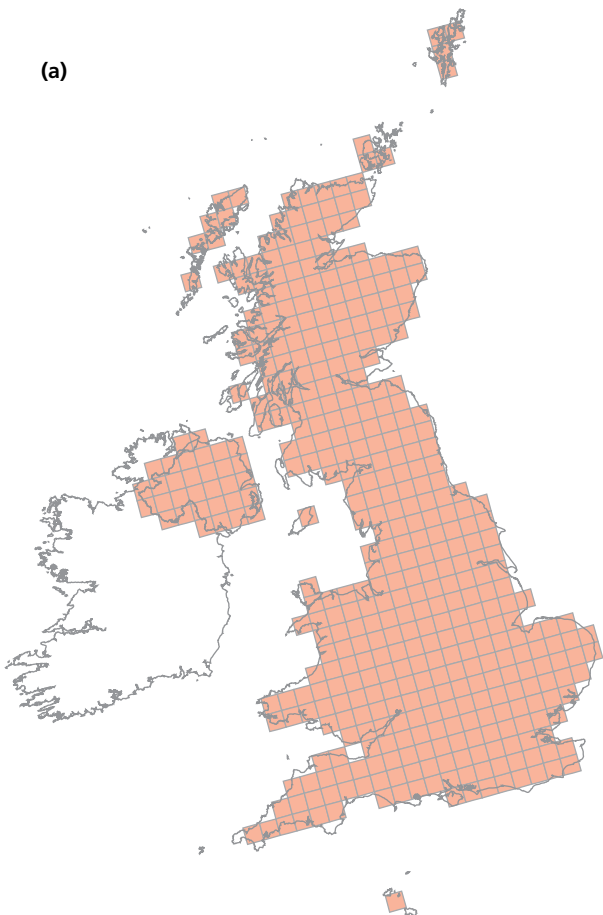
Variables include two measures of temperature extremes (high and low percentiles) and one precipitation extreme. For most variables, changes are given for three **temporal averaging periods**: month, season and year. Additional projections at daily and hourly resolution, consistent with the probabilistic projections, are available from a weather generator, described later in this report.

The **spatial resolution** of the projections over land areas is 25 km (Figure 7a), including islands large enough to be seen at this resolution. Because it is not possible for users to infer projections for larger regions by combining those from a number of individual 25 km squares, we also provide probabilities of change for two different sets of regions. The first of these (Figure 7b) is referred to for simplicity as *administrative regions* and encompasses the countries of Wales, Northern Ireland and Scotland (the latter subdivided into three climate regions), the nine administrative regions of England, together with the Isle of Man and a single grid square for the Channel Islands. The second set of regions is composed of river basins, based on those within the Water Framework Directive; these are shown in Figure 7(c). Lastly, probabilistic projections of change over the oceans surrounding the UK are not available at 25 km resolution from UKCP09, but instead are averaged over nine marine regions (Figure 7d). The names of the marine regions have been chosen specifically for the convenience of this report, and hence may not be geographically or politically correct.

| Variables over land areas |
|--|
| Mean temperature |
| Mean daily maximum temperature |
| Mean daily minimum temperature |
| 99th percentile of daily maximum temperature in a season (<i>Warmest day of the season</i>) |
| 1st percentile of daily maximum temperature in a season (<i>Coolest day of the season</i>) |
| 99th percentile of the daily minimum temperature in a season (<i>Warmest night of the season</i>) |
| 1st percentile of daily minimum temperature in a season (<i>Coldest day of the season</i>) |
| Precipitation rate |
| 99th percentile of daily precipitation rate in the season (<i>Wettest day of the season</i>) |
| Specific humidity |
| Relative humidity |
| Total cloud |
| Net surface long wave flux |
| Net surface short wave flux |
| Total downward short wave flux |
| Mean sea level pressure |
| Variables over marine regions |
| Mean air temperature |
| Precipitation rate |
| Total cloud |
| Mean sea level pressure |

Table 1: Climate variables for which changes are available in the UKCP09 probabilistic projections over land areas, and over the nine marine regions.

Figure 7 (opposite): Areas over which probabilistic projections are available — (a) the 25 km grid, (b) the 16 administrative regions, (c) the 23 river-basin regions, (d) the 9 marine regions.



Projections are given averaged over each of seven future overlapping 30-yr time periods, stepped forward by a decade, starting with 2010–2039. The use of 30-yr time periods reduces the effect of uncertainty due to natural internal variability. These future time periods are referred to for simplicity by their middle decade, starting from the 2020s (2010–2039) and ending with the 2080s (2070–2099). All changes are expressed relative to a modelled 30-yr baseline period of 1961–1990. Note that, by 2009, a significant proportion of the time between the baseline period and future time periods has already elapsed, so the changes should not be referred to as “from today’s climate”.

For some variables, UKCP09 also makes available probabilistic projections of future climate over land areas, also at 25 km resolution, in addition to those of the change in climate. This is done by combining probabilistic projections of climate change with the corresponding baseline (1961–1990) climate taken from observations. For marine regions, only climate change projections are available, and not projections of future climate.

As explained in Section 3, projections are given corresponding to three future emissions scenarios — Low, Medium and High. In UKCIP02 four emissions scenarios were used; two of them (Low and High) are the same as the corresponding scenarios in UKCP09. Factors such as inertia in the climate system mean that climate change over the first two or three decades from now is relatively insensitive to emissions. However, after the 2040s, projections based on different emissions scenarios increasingly diverge.

Box 2: Confidence in climate projections

There is a cascade of confidence in climate projections. There is very high confidence in the occurrence of global warming due to human emissions of greenhouse gases. There is moderate confidence in aspects of continental scale climate change projections. The 25 km scale climate change information is indicative to the extent that it reflects the large-scale changes modified by local conditions. There is no climate change information in the 5 km data beyond that at 25 km. All that can be produced is a range of examples of local climates consistent with current larger-scale model projections. The confidence in the climate change information also depends strongly on the variable under discussion. For example, we have more confidence in projections of mean temperature than we do in those of mean precipitation.

The probabilities provided in UKCP09 quantify the degree of confidence in projections of each variable, accounting for uncertainties in both large scale and regional processes as represented in the current generation of climate models. However, the probabilities cannot represent uncertainties arising from deficiencies common to all models, such as a limited ability to represent European blocking. The fact that the UKCP09 projections are presented at a high resolution for the UK should not obscure this, and users should understand that future improvements in global climate modelling may alter the projections, as common deficiencies are steadily resolved.

Box 3: How are probabilistic projections presented and how should they be interpreted?

What are PDFs and CDFs?

The provision of probabilistic projections is the major improvement which the UKCP09 brings to users. However, to utilise these appropriately, it is essential that users have a good understanding of what they mean and how they are communicated.

Probabilistic projections assign a probability to different possible climate change outcomes, recognising that (a) we cannot give a single answer and (b) giving a range of possible climate change outcomes is better, and can help with making robust adaptation decisions, but would be of limited use if we could not say which outcomes are more or less likely than others.

Within any given range of plausible climate changes, we cannot talk about the absolute probability of climate changing by some exact value — for example a temperature rise of exactly 6.0°C. Instead we talk about the probability of climate change being less than or greater than a certain value, using the Cumulative Distribution Function (CDF). This is defined as the probability* of a climate change being less than a given amount. The climate change at the 50% probability level is that which is as likely as not to be exceeded; it is properly known as the median, but in UKCP09 we refer to it by the more user-friendly name of *central estimate*. In Figure 8(a), the CDF (a hypothetical example at a certain location, by a certain future time period, for a given month of the year, under a particular emissions scenario) shows that there is a 10% probability of temperature change being less than about 2.3°C and a 90% probability of temperature change being less than about 3.6°C. In line with IPCC, we adopt the terminology *very likely* to refer to 90% probability and *very unlikely* to refer to the 10% probability. Thus, in Figure 8(a), we say that it is very unlikely that the temperature rise will be less than 2.3°C and very likely that it will be less than 3.6°C.

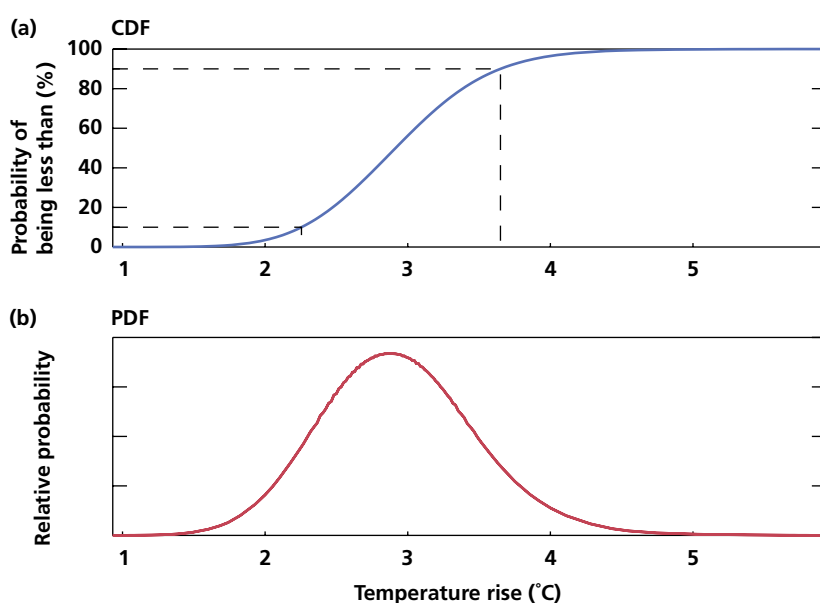


Figure 8: (a) Cumulative distribution function of temperature change for a hypothetical choice of emission scenario, location, time period and month. (b) Corresponding probability density function for this hypothetical case.

* Probabilities in CDFs are conventionally taken to range between 0 and 1, although we refer to them here as percentages, between 0 and 100%

These statements conventionally concern the probability of change being less than a given threshold, but of course we can turn them around to give the probability of exceeding that threshold. Thus the CDF in Figure 8(a) also shows that there is a 90% probability (very likely) that temperature change will exceed about 2.3°C and a 10% probability (very unlikely) that the temperature change will exceed about 3.6°C.

The CDF would be useful for those who want to know the probability of climate change being less than some threshold where an impact of interest starts to occur. However, the CDF is not useful for understanding the relative probability of different specific outcomes. The Probability Density Function (PDF) is an alternative representation of the same distribution which is a useful visualisation of the relative likelihood of different climate outcomes. For a given value of climate change, the CDF is the area under the PDF to the left of that value of climate change. As the CDF has a maximum value of 100%, the area under the PDF curve cannot be more than 100%.

As probability is represented by the area under a PDF curve, the y-axis in Figure 8(b) is referred to as a probability density, with units of *per °C*. However, the PDF can be thought of more simply in relative terms by comparing the ratios of probability density for different outcomes. For instance, as the probability density at 2.9°C is about 0.7 (*per °C*) and the probability density at 3.8°C is about 0.2 (*per °C*), then a temperature change of 2.9°C is about 3.5 times more likely than one of 3.8°C. Hence, for simplicity, PDF graphs from the User Interface are all labelled *relative probability* rather than *probability density (per °C)*.

The hypothetical distribution shown in Figure 8(b) is smooth and almost symmetrical; in practice the UKCP09 distributions vary in shape, dependent on how the effects of uncertain climate system processes combine to produce different projections for different variables, time periods and locations.

How do we interpret probability in UKCP09?

It is very important to understand what a probability means in UKCP09. The interpretation of probability generally falls into two broad categories. The first type of probability relates to the expected frequency of occurrence of some outcome, over a large number of independent trials carried out under the same conditions: for example the chance of getting a five (or any other number) when rolling a dice is 1 in 6, that is, a probability of about 17%. This is not the meaning of the probabilities supplied in UKCP09, as there can only be one pathway of future climate. In UKCP09, we use the second type (called *Bayesian probability*) where probability is a measure of the degree to which a particular level of future climate change is consistent with the information used in the analysis, that is, the evidence. In UKCP09, this information comes from observations and outputs from a number of climate models, all with their associated uncertainties. The methodology which allows us to generate probabilities is based on large numbers (*ensembles*) of climate model simulations, but adjusted according to how well different simulations fit historical climate observations in order to make them relevant to the real world. The user can give more consideration to climate change outcomes that are more consistent with the evidence, as measured by the probabilities.

Hence, Figure 8(a) does not say that the temperature rise will be less than 2.3°C in 10% of future climates, because there will be only one future climate; rather it says that we are 10% certain (based on data, current understanding and chosen methodology) that the temperature rise will be less than 2.3°C. One important consequence of the definition of probability used in UKCP09 is that the probabilistic projections are themselves uncertain, because they are dependent on the information used and how the methodology is formulated. At the end of Section 5 we discuss the uncertainty in the probabilistic projections in more detail and Annex 2 of the **Climate change projections report** explores their robustness to changes in evidence and methodology.

The UKCP09 probabilistic projections allow us in principle to look at changes which have a very small, or very large, probability; **we advise against this**. The robustness of the projections decreases as we go towards the extremes (tails) of the distribution. So, for example, data at a given probability (say 95%) may be relatively robust for one variable (e.g. seasonal mean temperature) but less robust in the case of another (e.g. wettest day of the season). Although we have different levels of confidence in different variables, as a general guideline we suggest that users should be able to use the cumulative distribution from the 10% to the 90% probability levels, but outside this range, up to 1% and 99%, only with caution.

Changes in daily climate

Changes in daily climate, such as the frequency of hot or very wet days, are likely to be more significant for many climate impacts than changes in monthly or seasonal averages. Whilst, as we saw in the previous section, we are not able to project changes in storm tracks and anticyclones with confidence, we can project how the characteristics of daily time series (weather) could be affected by changes in the more basic aspects of future climate, such as monthly mean temperature and precipitation and other aspects of their distributions, which we have more confidence in projecting.

In order to provide consistency between impact studies, we have incorporated a weather generator in UKCP09 to supply plausible realisations of how future daily time series could look, consistent with changes in the characteristics of monthly-average climate. The UKCP09 Weather Generator provides such synthetic time series of temperature (mean, maximum and minimum), precipitation, relative humidity, vapour pressure, potential evapotranspiration (PET) and sunshine (from which we also estimate diffuse and direct downward solar radiation) at a resolution of 5 km, for each of the three emission scenarios and each of the future 30-yr time periods — 2020s, 2030s, etc.

As pointed out in Box 2, there is a cascade of confidence in climate projections at different scales, and the UKCP09 Weather Generator does not add any additional climate change information over that which is present in the probabilistic projections. The 5 km scale is used to add local topographic information (e.g. hills, valleys) and it is based on observed data which is representative of that scale. Users can average changes from a small number (up to 40) of 5 km squares to get changes over a bigger area.

How does the Weather Generator work?

Weather generators have been used for many years in studies of flood risk and water resources. The Weather Generator works by generating series of numbers representing the climate variables. These numbers have a random element, but they are related to each other statistically, and are governed by their overall properties (e.g. the average is fixed to a particular value). The Weather Generator initially predicts daily precipitation and uses this to derive other variables, for example temperature. The statistical relationships between precipitation and other climate variables are derived from observations for a particular time of year. This method has been found to work well for a wide range of variables and conditions, can reproduce seasonality and sequences of weather, and can even reproduce the statistics of some extreme events reasonably well. For future climates, the statistics used to set up the weather generator are *perturbed* using change factors derived from the probabilistic climate projections — these are not just changes of average values but also of the variability. The Weather Generator should be run not just once but at least 100 times, so that the probabilistic nature of these change factors is reflected in the generated daily time series. For further information, see the User Guidance (<http://ukclimateprojections.defra.gov.uk>).

The Weather Generator is also able to construct synthetic hourly time series for precipitation, temperature, vapour pressure, relative humidity and sunshine for future time periods. This is a disaggregation of daily data and, again, does not provide any new climate change information.

Weather generator outputs do not represent actual weather which has occurred or is predicted to occur on specific real days or hours (e.g. a historical date, or a forecast for a real date in the future). Rather, they are just statistically credible representations of what may occur given a particular future climate. The purpose is to provide information on types of events that occur at this time scale such as heatwaves, frosts, and dry spells.

A rather different type of projection at a daily resolution is also available from transient experiments (that is, run continuously from 1950 to 2099) from 11 variants of the 25 km resolution Met Office Hadley Centre regional climate model. Unlike those from the Weather Generator, the daily time series are spatially coherent and physically consistent across the whole of the UK. However, because they come only from Met Office Hadley Centre models and hence do not explore as wide a range of uncertainty as the probabilistic projections, they are not part of UKCP09. Data is available, however, from the Climate Impacts Link Project website (<http://badc.nerc.ac.uk/data/link>).

Comparison of information in UKCIP02 and UKCP09

Table 2 (opposite) outlines the main differences between what is included in, and available from, the UKCP09 projections over land areas of the UK and those issued in 2002 (UKCIP02); comparisons between the actual projections from each are in Section 5. Projections over oceans are available in UKCP09 for predefined marine regions rather than for 50 km squares as in UKCIP02.

| | UKCIP02 | UKCP09 |
|--|---|---|
| Variables | 17 variables: see Table A.1 of UKCIP02. | Probabilistic projections as for UKCIP02 but minus snow, soil moisture and surface latent heat flux. See Table 1. Projections from 11 variants of the Met Office Hadley Centre regional climate model (RCM) are described in Chapter 5 of the <i>Climate change projections</i> report. |
| Spatial resolution? | 50 km. | 25 km for probabilistic projections, 5 km for the Weather Generator, but there is no additional climate change signal over that at 25 km resolution. |
| Data over larger areas possible? | Yes, by users averaging multiple grid squares. | Yes, data averaged over administrative regions, river basins and marine regions is provided. |
| Coherence between grid squares? | Yes. | No. |
| Emissions uncertainty explored? | Yes, by showing projections for 4 emissions scenarios. | Yes, by showing projections for 3 emissions scenarios. |
| Modelling uncertainty explored? | No, all projections are from Met Office Hadley Centre models. | Yes, within the probabilistic projections. |
| Natural internal variability explored? | Partly, by having 3 model runs with different initial conditions. | Yes, included in the probabilistic projections. |
| Pattern-scaling and downscaling uncertainty? | Not included. | Yes, included in the probabilistic projections. |
| Which 30-yr future time periods? | 2020s, 2050s, 2080s. | 2020s, 2030s, 2040s, 2050s, 2060s, 2070s, 2080s. |
| Temporal averaging? | Monthly, seasonal, annual. | Monthly, seasonal, annual. |
| Daily time series? | Yes, for 2071–2100. | Yes (a) synthetic daily data for 9 variables from the Weather Generator, but there is no climate change signal additional to that at monthly resolution in the probabilistic projections, (b) continuous daily model output 1951–2099 from 11 variants of the Met Office Hadley Centre RCM. |
| Hourly time series? | No. | Yes, synthetic hourly data from weather generator, but there is no additional climate change signal. |
| Climate change only or future climate? | Climate change. | Climate change and future climate. |
| Graphics available in addition to those in Science Report? | Additional maps (including regions) on UKCIP website. | (a) pre-prepared maps and graphs on UKCP09 website, (b) custom graphics from User Interface. |
| Carbon cycle feedback? | No. | Yes. |

Table 2: A comparison between what is included in, and available from, the UKCIP02 and UKCP09 projections.

5 Some projections of changes in the UK climate

In this section we show some probabilistic projections of changes in a few of the most commonly used variables and seasons, for the future time period of the 2080s and the Medium emissions scenario, as examples of the sort of information available in UKCP09:

- Change in mean temperature, winter and summer means, (25 km resolution and marine regions)
- Change in mean daily maximum temperature, summer, (25 km resolution and administrative regions)
- Change in precipitation, annual, winter and summer means (25 km resolution)
- Change in annual mean precipitation (river basins)

A short summary of any significant pattern is given for central estimates of changes (that is, those at the 50% probability level) by the 2080s under the Medium emissions scenario, although geographical patterns can most easily be seen from the maps. Other time periods and emissions scenarios, and particularly probability levels, may have different patterns.

Because the choice of projections depends upon the individual user's attitude to risk, a full summary of results is not provided here. Advice on how to access projections that relate to users' own needs is provided in the User Guidance.

A comprehensive set of pre-prepared maps and graphs can be seen on the UKCP09 website, which provides many more illustrations of projections than can be shown in a report, e.g. maps for other future time periods and emissions scenarios. And, because pre-prepared graphics are not always sufficient, a User Interface, and accompanying guidance, has been developed in response to user consultations, to allow users to download the underlying datasets, to access projections for other variables, probability levels, locations, time periods, temporal and spatial averages and emissions scenarios.

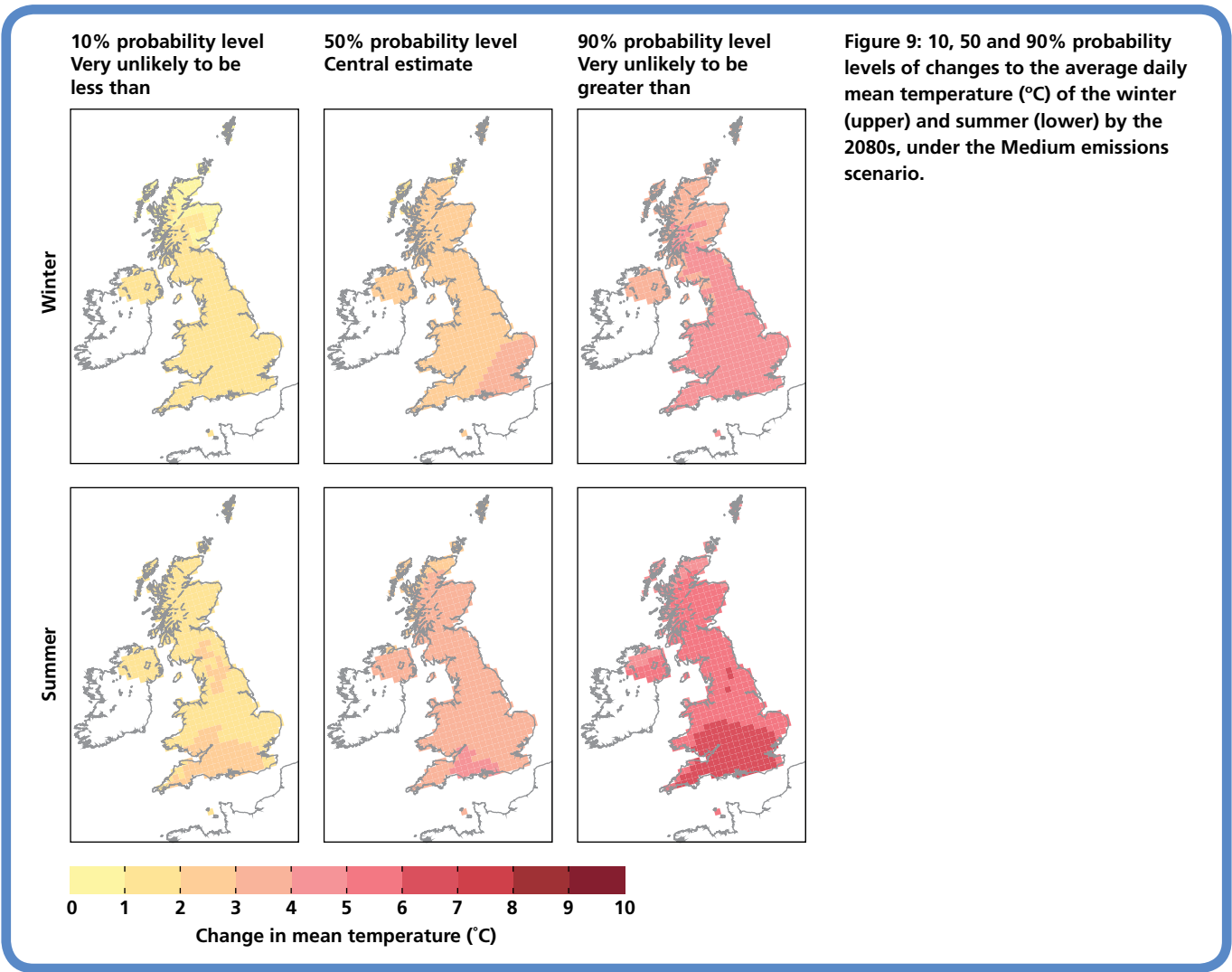
This section also shows examples of changes in daily climate from the UKCP09 Weather Generator.

Projections of change in mean temperature

Figure 9 shows that, in winter, the central estimates of change are projected to be generally between 2 and 3°C across most of the country, with slightly larger changes in the south east and slightly smaller in the north west of Britain. In summer a more pronounced south to north gradient exists with changes in some parts of southern England being just over 4°C and in parts of northern Scotland about 2.5°C.

Projected changes in winter and summer seasonal mean air temperature over marine regions

Figure 10 shows projections of changes into the seasonal-mean air temperature over the nine marine regions around the UK, at the 10, 50 and 90% probability levels. Changes in temperature in all cases are larger in the south and smaller in the north; this pattern is also seen over land and reflects the degree to which areas are affected by proximity to continents or open oceans. Note that, even by the 2080s under the highest emission scenario, the 10% probability level shows projected reductions in mean air temperature in the Atlantic NW Approaches in both seasons; in summer, cooling also extends to the Scottish Continental Shelf area. This reflects the effect on temperatures of the large natural internal variability of climate; at the 10% probability level, this natural variability could more than offset the rather modest warming from human activities in these regions.



Projected changes to the mean daily maximum temperature in summer

Figure 11 shows that, in summer, central estimates of changes to mean daily maximum temperature show a gradient between parts of southern England, where they can be 5°C or more, and northern Scotland, where they can be somewhat less than 3°C. In Figure 12, the same information as in Figure 11 is given averaged over administrative regions rather than at 25 km resolution.

Projected changes to annual-, winter- and summer-mean precipitation, 2080s

The central estimates of changes in annual mean precipitation (Figure 13) are within a few percent of zero everywhere. In winter, precipitation increases are in the range +10 to +30% over the majority of the country. Increases are smaller than this in some parts of the country, generally on higher ground. In summer, there is a general south to north gradient, from decreases of almost 40% in SW England to almost no change in Shetland.

Note that the changes at 10, 50 and 90% probability levels not only have different magnitudes, but can also be in different directions (that is, can become wetter or drier). Thus summer precipitation (the lowest 3 maps in Figure 13) is projected to decrease almost everywhere in the UK at the 10 and 50% probability levels, but increase almost everywhere at the 90% probability level. In other words, using a specific area as an example, it is very unlikely that Northern Ireland in summer will dry by more than 30–40%, and very unlikely that it will be more than 0–10% wetter, with a central estimate of 10–20% drier.

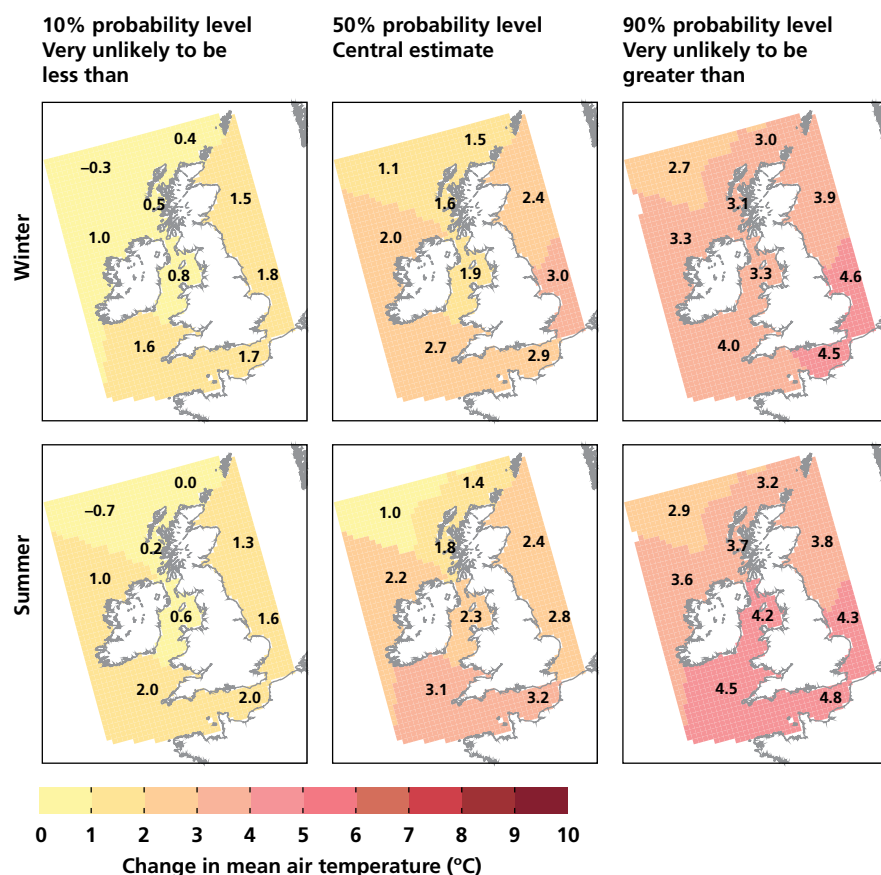


Figure 10: 10, 50 and 90% probability levels of changes to winter-mean (top) and summer-mean (bottom) air temperature over marine regions under Medium emissions by the 2080s. Each marine region is overprinted with its corresponding change in temperature (°C).

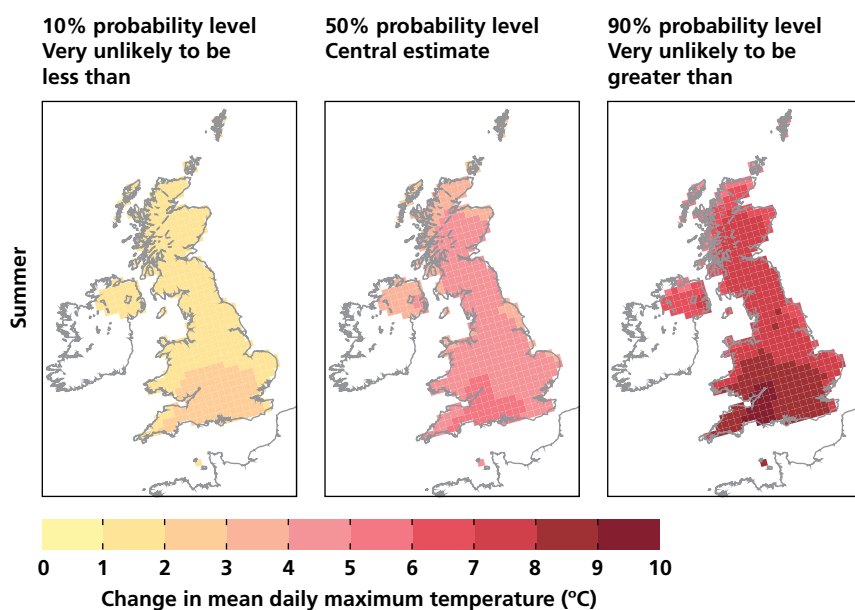


Figure 11: 10, 50 and 90% probability levels of changes to mean daily maximum temperature in summer, by the 2080s, under the Medium emissions scenario.

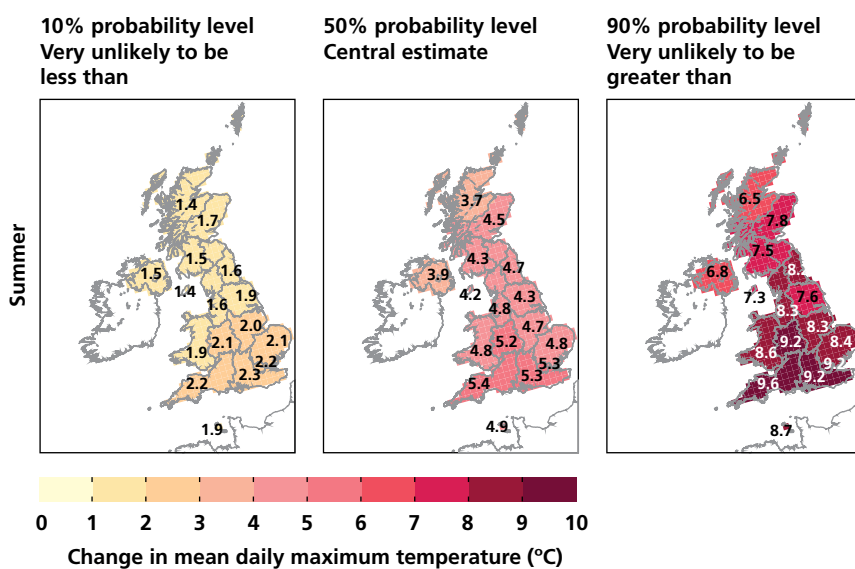


Figure 12: As For Figure 11, but showing changes to summer mean daily maximum temperature averaged over administrative regions.

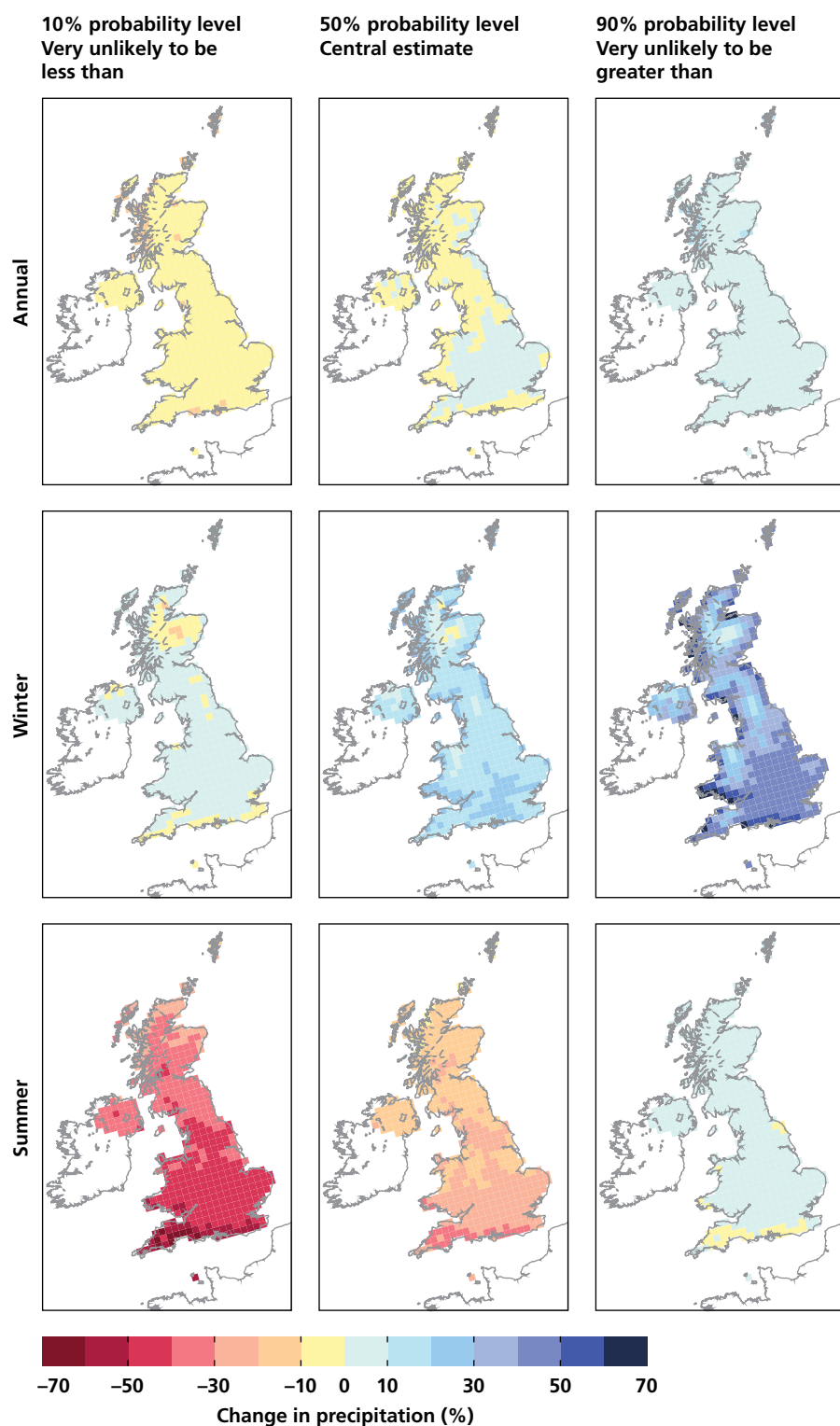


Figure 13: Changes (%) in annual (top), winter (middle) and summer (bottom) mean precipitation at the 10, 50 and 90% probability levels, for the 2080s under the Medium emissions scenario.

Central estimates of changes in precipitation on the wettest day of the winter by the 2080s with Medium emissions range from zero in parts of Scotland to +29% in parts of England. Corresponding changes in precipitation on the wettest day of the summer range from –9% in parts of southern England to +25% in parts of Scotland.

In Figure 14, we show changes in annual mean precipitation averaged over river basins.

Changes in other variables

In addition to the temperature and precipitation variables discussed above, UKCP09 gives changes in a number of other variables. We summarise here changes in four of the most commonly used of these, by the 2080s under Medium emissions; projections are for the 50% probability level, followed in brackets by changes at the 10 and 90% probability levels.

- Downward shortwave radiation at the surface shows changes of only a few percent in winter. In summer it increases by up to +16 Wm⁻² (–2 to +37 Wm⁻²) in parts of southwest England and Wales, but changes by only a few Wm⁻² (–17 to +4 Wm⁻²) in parts of northern Scotland.
- Total cloud amount changes by only a few percent (–9 to +6%) in winter. It decreases, by as much as –18% (–33 to –2%), in parts of southern England, with smaller changes further north.
- Relative humidity decreases in summer in southern England, by as much as about –10% (–20% to zero); changes are smaller further north. In winter, changes are ± a few percent only across the UK.

Variables for which probabilistic projections proved not to be possible (snowfall rate, soil moisture, latent heat flux) are discussed later in this report.

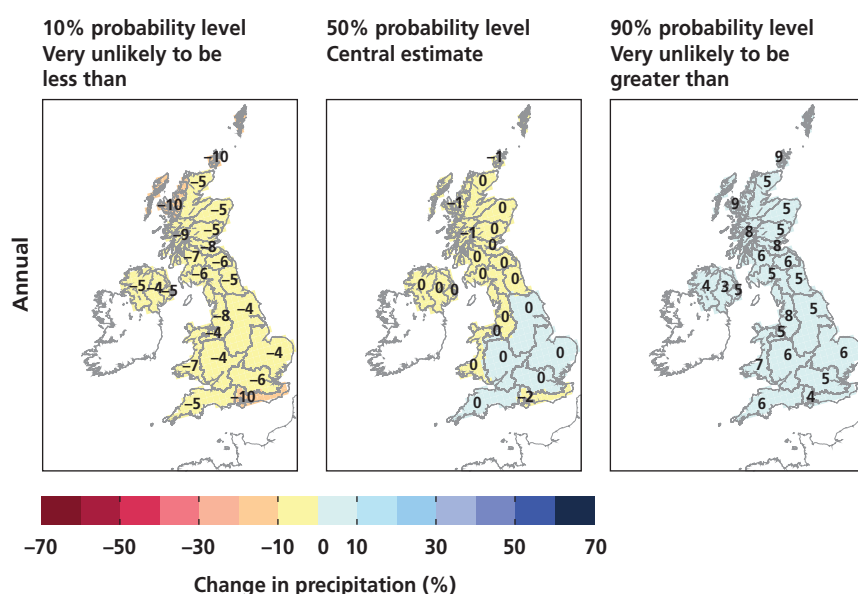


Figure 14: Changes to annual mean precipitation (%) at the 10, 50 and 90% probability levels, by the 2080s under Medium emissions, averaged over river basins.

Comparison between projections in UKCP09 and UKCIP02

It is instructive to compare the UKCP09 Projections with corresponding ones in UKCIP02. Figure 15 shows an example of a UKCP09 cumulative distribution of projected change in temperature, together with the single projection (for the same time period and emissions scenario, and the closest location) from UKCIP02. It can be seen that, in this example, the UKCIP02 projection represents a probability of about 56%, that is, in the UKCP09 projections it is 56% probable that the change in temperature will not exceed the UKCIP02 value. This sort of comparison may be useful to those who have previously used UKCIP02 in research and to inform policy, as they can see where within the new distribution the previous value lies. The graph also shows that the change projected by UKCIP02 lies within the wide range of possible outcomes projected by UKCP09, illustrating the need to account for uncertainties in planning and decision-making.

Comparisons between the two sets of projections can also be illustrated using maps of changes; those in Figures 16 and 17 are in seasonal mean temperature and precipitation, for summer and winter, for the 2080s under the High emissions scenario (which is the identical scenario in the two sets of projections). We show the single result from UKCIP02 alongside the 10, 50 and 90% probability levels in UKCP09. (Comparisons between changes in UKCIP02 and UKCP09 over ocean areas cannot easily be made, as the former are only available at 50 km resolution, and the latter only for marine regions.)

Having stressed above the need for users to consider the full robust range of uncertainty given in UKCP09, it is illustrative to compare the central estimate (50% probability) of UKCP09 changes with the single projection in UKCIP02, for the same (High) emissions scenario; this allows us to make the following qualitative comments:

- In the case of mean temperature, projected changes in UKCP09 are generally somewhat greater than those in UKCIP02.
- The summer reduction in rainfall in UKCP09 is not as great as that projected in UKCIP02.

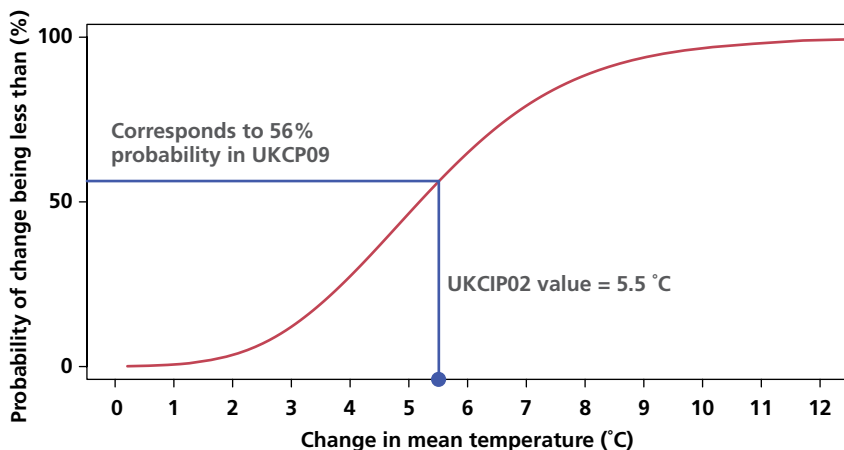


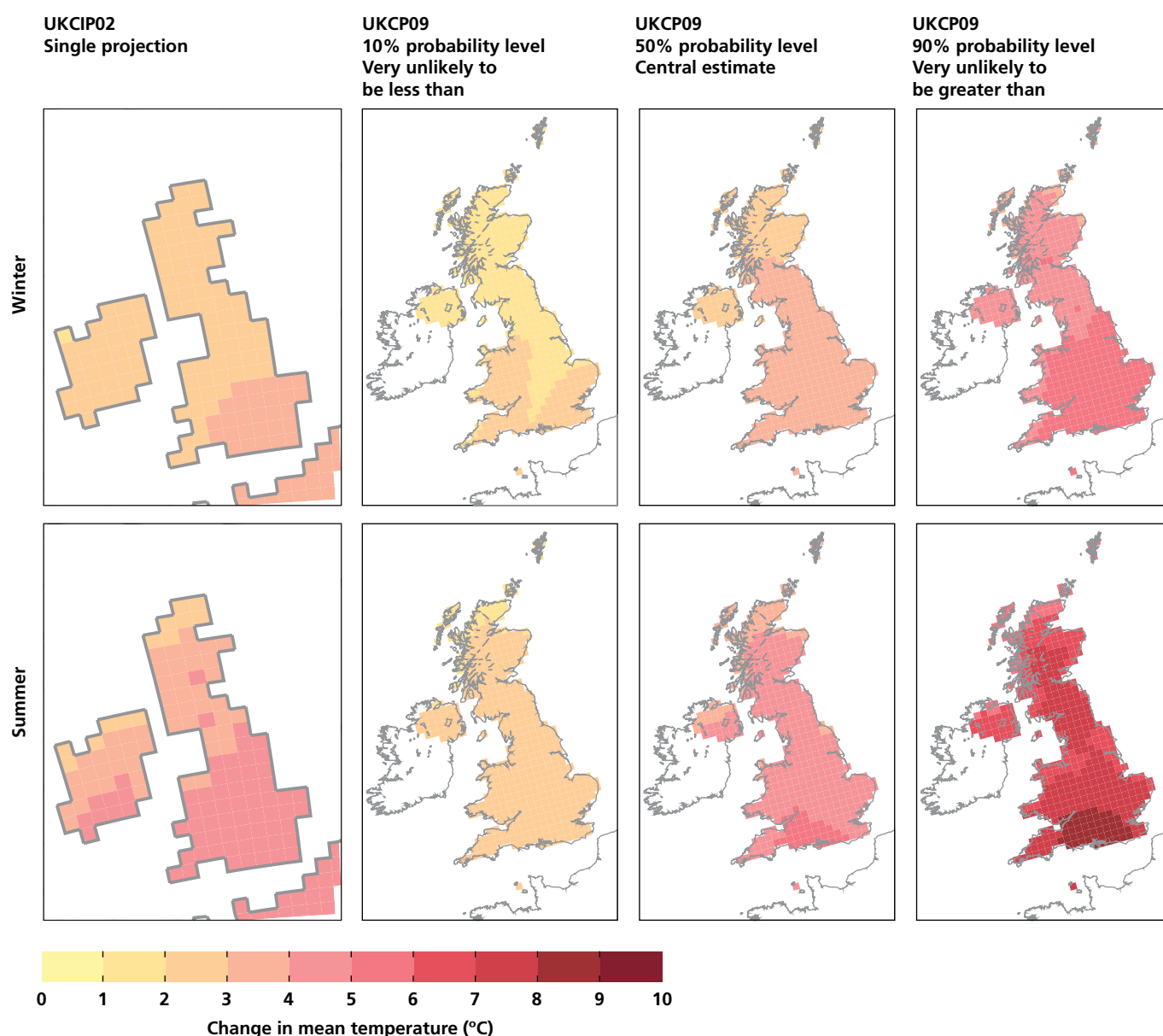
Figure 15: The CDF of temperature change for a 25 km square in Dorset, by the 2080s under High emissions. The blue circle shows the corresponding value from the nearest 50 km square in the UKCIP02 scenarios, and the blue lines show that this represents a probability in UKCP09 of about 56%.

- The range of increases in rainfall in winter seen in UKCP09 are very broadly similar to those in UKCIP02, although with a different geographical pattern. A few grid squares are projected to dry in winter in UKCP09; in UKCIP02 all areas were projected to be wetter.
- Small changes in cloud amount (not shown here) are projected in winter, as in UKCIP02. Projections of summer decreases in cloud are similar to those in UKCIP02.

For brevity, comparisons above are made only with the central estimate in UKCP09; however, users are advised to use the projections over the full robust range (i.e. 10–90%) of probability levels in adaptation decisions or when considering the need to update previous decisions based on UKCIP02.

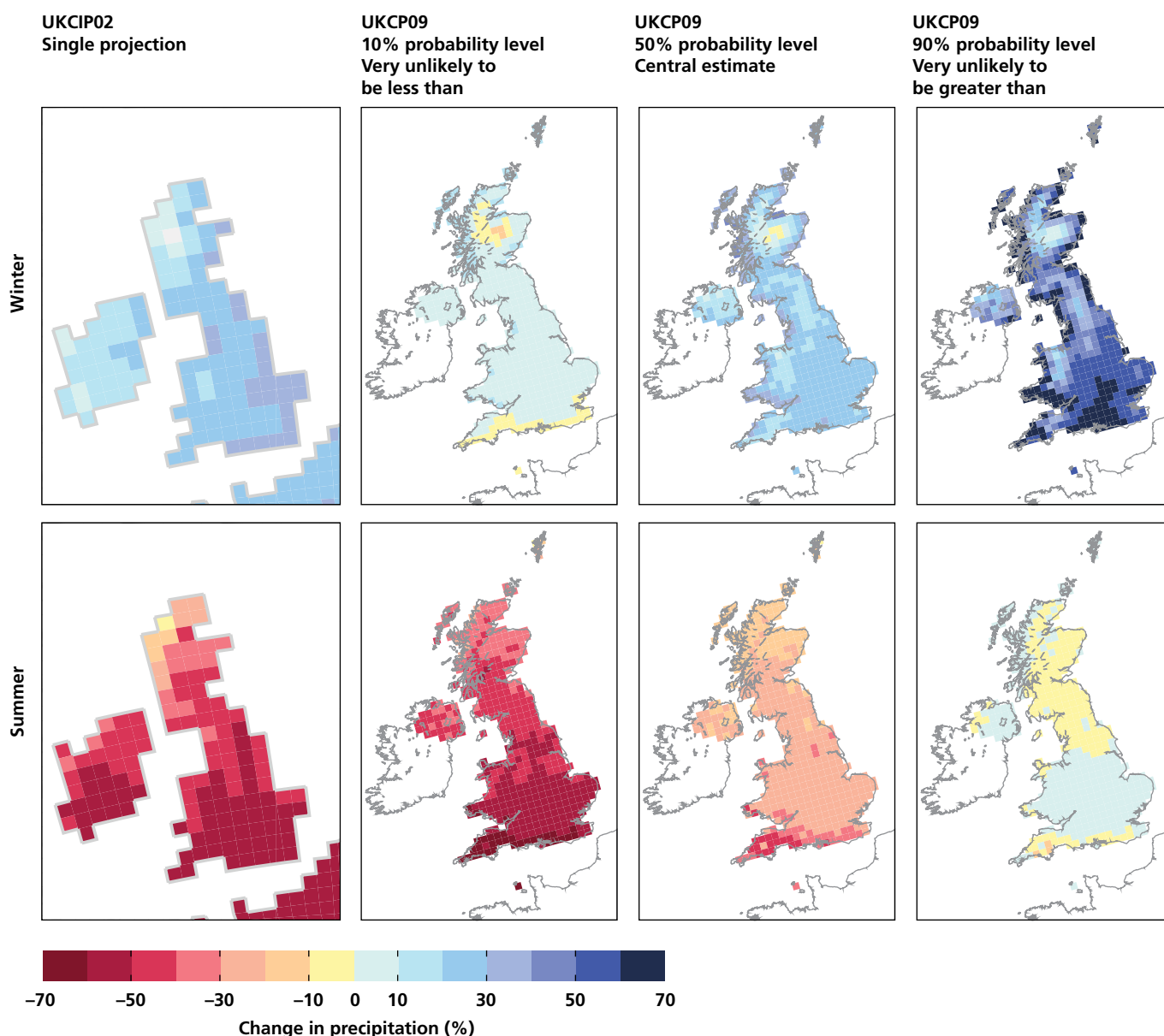
The reasons for the differences between the two sets of projections lie in the different model results and methodology which were used to derive them. UKCIP02 was derived using one (Met Office Hadley Centre) model, whereas

Figure 16: Comparison of changes in seasonal mean temperature, winter (top) and summer (bottom), by the 2080s under High Emissions scenarios, from the UKCIP02 report (far left panels) and as projected in UKCP09 (10, 50 and 90% probability level).



UKCP09 is derived from a large ensemble of variants of the Met Office Hadley Centre model, each member having different settings for model parameters controlling key physical processes, together with a smaller ensemble of other international models. In addition the UKCP09 Projections include the effects of land and ocean carbon cycle feedbacks and the uncertainties in the land component (estimated using large ensembles of both Met Office and alternative climate models) and also uncertainties associated with the statistical processing required to convert ensembles of climate model simulations into probabilistic projections; neither of these could be included in UKCIP02. Specific differences between changes in a particular variable in UKCIP02 and UKCP09 will generally have a number of complex contributory reasons. UKCIP02 projections should not be seen as some benchmark against which all successive projections must be compared and differences explained. The advent of new methodologies (allowing us to quantify uncertainty), and the inclusion of more recent knowledge (e.g. carbon cycle feedbacks) gives the UKCP09 Projections many advantages over those in UKCIP02, and it is strongly recommended that users no longer employ UKCIP02, in isolation.

Figure 17: As Figure 15 but for seasonal mean precipitation.



What effect do user choices have on the probabilistic projections?

The UKCP09 User Interface will enable users to choose to display and use projections over land for different:

- emissions scenarios (Low, Medium and High)
- future time periods (7 overlapping 30-yr periods from 2010–2039 to 2070–2099)
- spatial averaging (25 km grid square, average over an administrative region, river basin or marine region)
- temporal averaging (generally month, season, annual)
- geographical locations
- variables
- show change in climate, or (for some variables) future climate

The effect of many of these choices on the shape of the probability distribution (PDF) is shown in Chapter 4 of the *Climate change projections report*. In Figure 18 we show an example comparing the PDFs of the projected change in summer mean maximum temperature for the south east England administrative region. As we might expect, at corresponding probability levels, changes with High emissions are greater than those with Low emissions, although there is a great deal of overlap in the distributions, showing that the uncertainties associated with emissions, whilst important, do not dominate those associated with projecting climate response. Differences may be more or less pronounced with other variables, time periods, etc.

Other ways of displaying probabilistic projections

The User Interface can also be used to explore how projections change with time over the course of the century, using a *plume of probability*. Essentially, this takes a number of probability levels from the CDFs for each of the seven future time periods, and presents them as a time series, with straight lines for each of the probability levels joining the calculated values. We show an example in Figure 19 of changes with time of summer mean temperature in Central London under a High emissions scenario. Thus the top line in the figure shows how the temperature change that is very unlikely to be exceeded increases decade by decade through the century, the middle line shows the central estimate, etc.

The User Interface also allows the joint probability of changes in some (but not all) combinations of two variables to be calculated. These can be used to explore specific impacts on targets (e.g. crops) which are vulnerable to changes in both variables; the User Interface can create plots of these distributions. Figure 20 shows an example for changes in precipitation and in mean temperature. Joint probability values are shown by the red contour lines, and have been multiplied by 1000 to make them more readable. So, referring to the figure, there is a joint probability of about $2/1000 = 0.0002$ of a simultaneous change of 1°C^* in temperature and -50% in precipitation. Similarly, there is a joint probability of about $18/1000 = 0.0018$ of the same precipitation change but a 5°C temperature change, that is some 9 times greater than for the 1°C change.

* Strictly speaking, the changes would be over small intervals around 1°C and -50% .

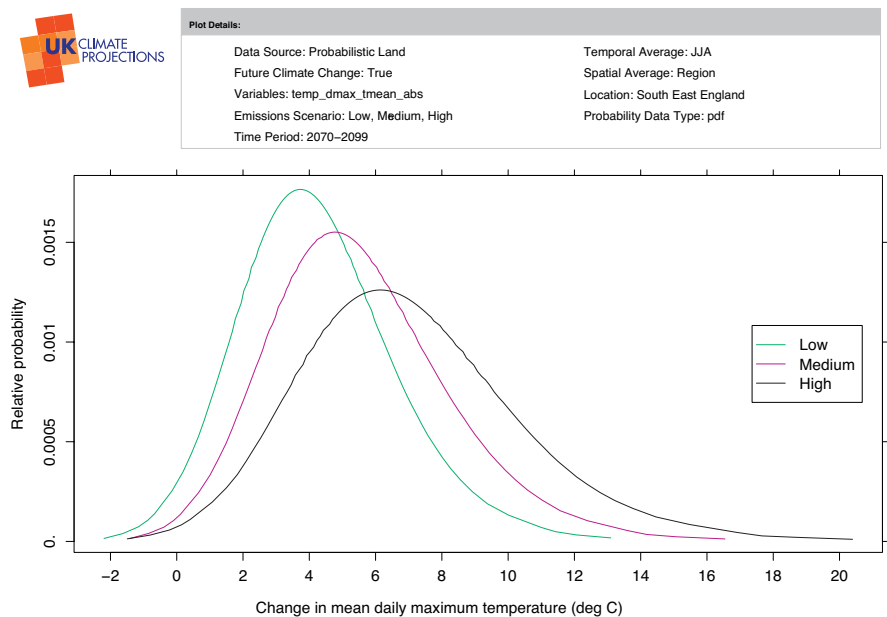


Figure 18: PDFs of change in summer-mean daily maximum temperature in South East England for the Low (green), Medium (purple) and High (black) emissions scenarios, for the 2080s. (Note that this is an example graphic taken directly from the User Interface, showing the plot details in a box above the plot.)

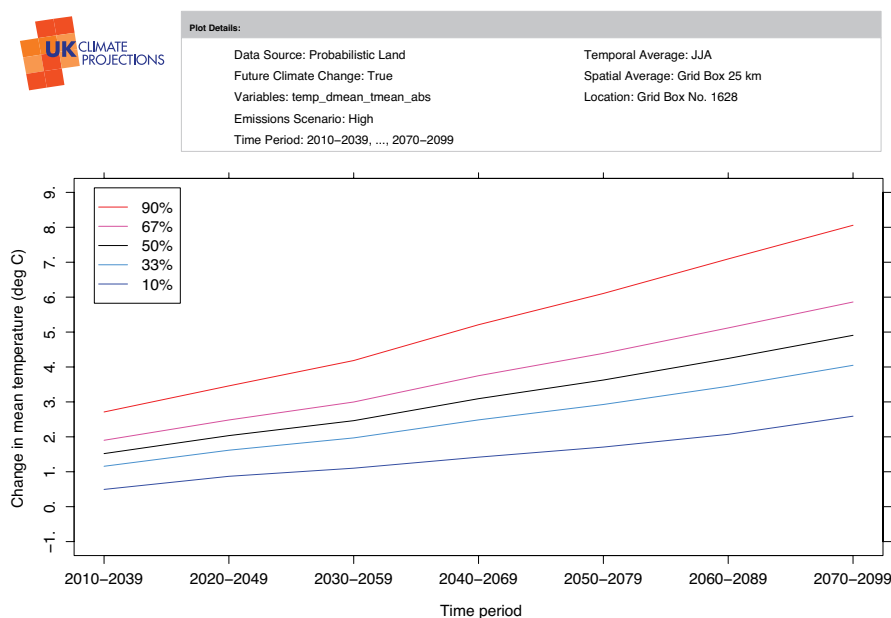


Figure 19: The progression from the 2020s to the 2080s of changes in summer mean temperature under the High emissions scenario, for a single 25 km grid square in Central London. Changes at probability levels of 10, 33, 50, 67 and 90% are indicated by different colours. (This plot is direct from the User Interface.)

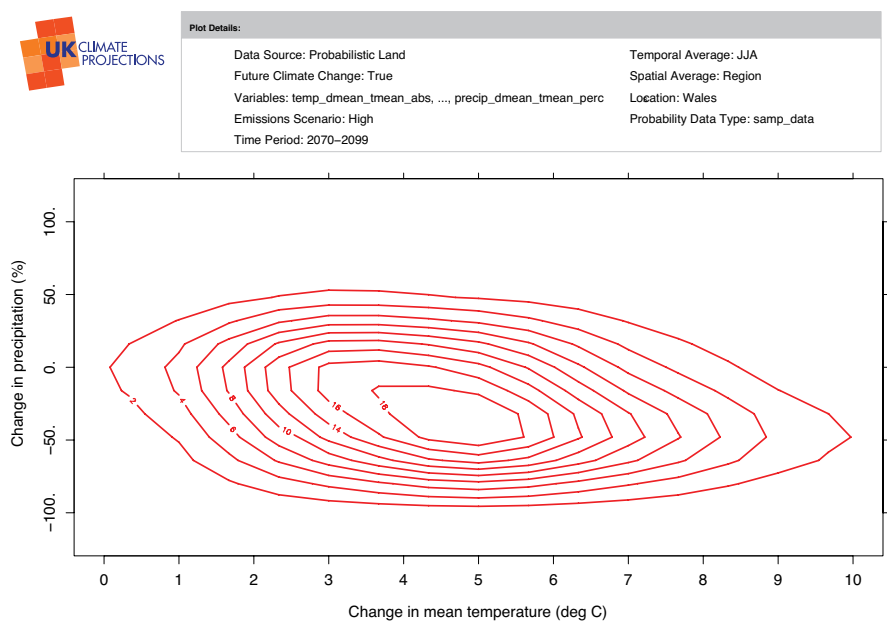


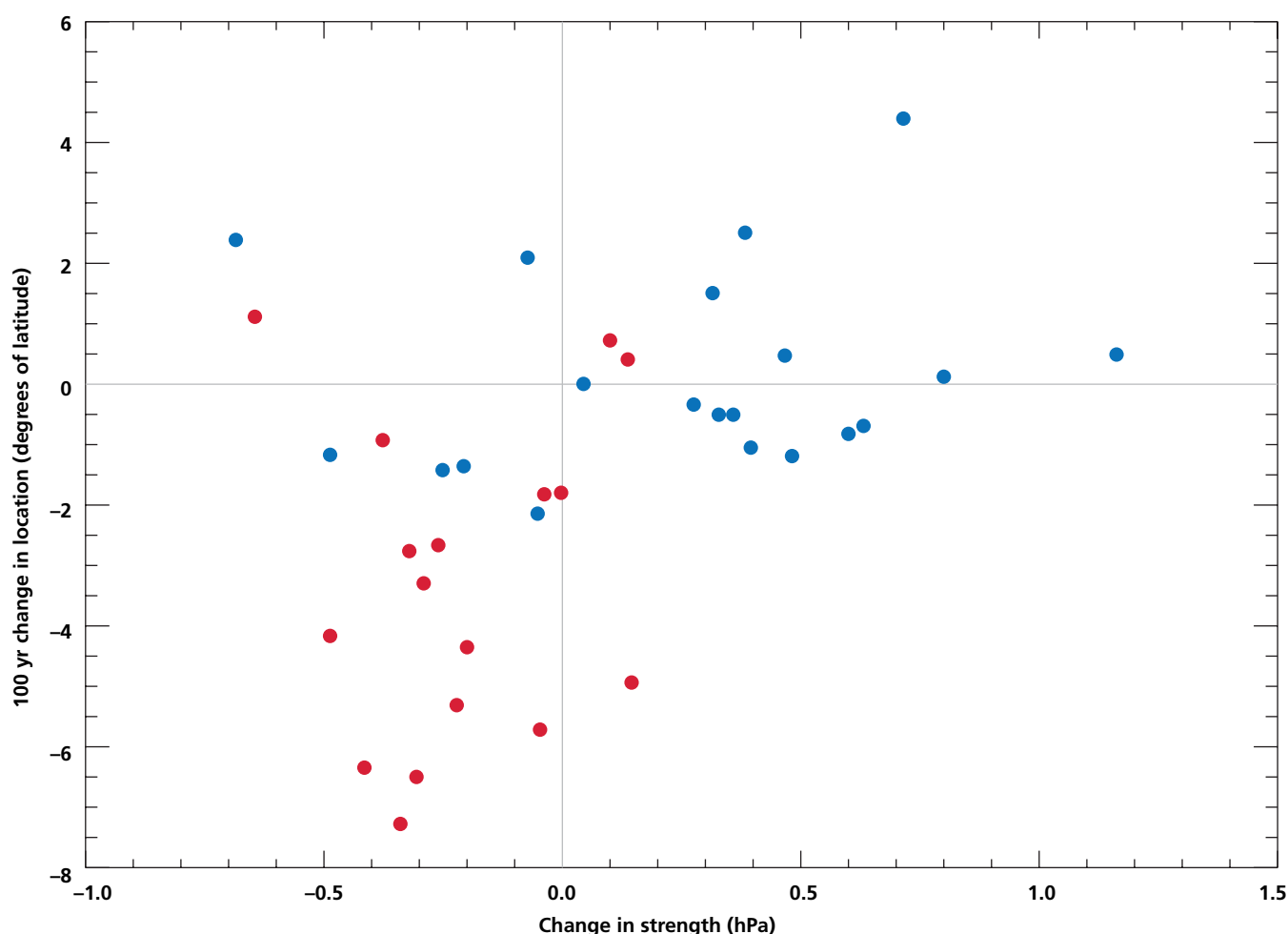
Figure 20: The joint probability distribution of changes in summer-mean temperature and that in precipitation, by the 2080s under the High emissions scenario, for the administrative region of Wales. The red lines are contours of relative probability. (This plot is direct from the User Interface.)

Storm tracks, wind and anticyclones

Figure 21 shows changes in both the latitude and the strength of the centre of the North Atlantic storm track near the UK, by the 2080s under the Medium emissions scenario, from 17 variants of the Met Office Hadley Centre global model, chosen to sample a wide range of uncertain model parameters, and from 20 similar alternative climate models. The Met Office Hadley Centre models (red dots) have a tendency to project the storm track weakening slightly and moving further south. The alternative models show, in general, less change in the position of the track, but a wide range of changes in strength. Furthermore, a comparison of each model's current storm track with observations shows an equally wide range of differences between model simulations and reality. These differences between individual models, and also between different types of model ensemble, indicate that robust projections of changes in storm track are not yet possible.

Anticyclones can persist over the UK for days or even weeks. They are associated with low wind speeds and, often, clear skies, conditions which can lead to high levels of pollution. In winter they can lead to cold spells at night and in summer they are responsible for heatwaves. Unfortunately, just as with storm tracks, model projections do not give a clear picture of changes to anticyclones. There is no compelling evidence that the frequency, duration or intensity of those affecting the UK will change markedly either way, although neither can it be ruled out.

Figure 21: Projected changes in the latitude (y axis) and strength (x axis) of the Atlantic storm track near the UK, by the 2080s under a Medium emissions scenario. The red dots are changes from members of the Met Office Hadley Centre perturbed physics ensemble; blue dots are those from alternative climate models.



Variables for which probabilistic projections cannot be provided

For a variety of different reasons it has not been possible in UKCP09 to provide probabilistic projections of future changes to soil moisture, snowfall rate or latent heat flux.

In the absence of a UKCP09 probabilistic projection for these four variables, there are three possible alternative sources of projections of transient changes during the 21st century:

- the 17-member ensemble of variants of the Met Office Hadley Centre GCM
- the 11-member ensemble of variants of the Met Office Hadley Centre RCM
- the ensemble of other global climate models, available from the PCMDI website

The data from other global climate models, and that from the 17-member Met Office Hadley Centre GCM ensemble, is at a relatively coarse resolution. The Met Office Hadley Centre RCM has a finer resolution (25 km) and hence provides more information on possible regional variations across the UK. The range of modelling uncertainties explored in the 17-member Met Office Hadley Centre GCM ensemble, and the 11-member Met Office Hadley Centre RCM ensemble, is not as wide as that explored in the variables for which probabilistic projections are provided in UKCP09. The RCM data is only available for the Medium emissions scenario.

Each type of data has advantages and disadvantages. In the case of snowfall rate and wind speed, we recommend the use of changes from the 11-member Met Office Hadley Centre RCM ensemble in the first instance. Changes by the 2080s in the winter mean snowfall rate, averaged over the 11-RCM ensemble are also shown in Figure 22; typically there are reductions of 65–80% over mountain areas and 80–95% elsewhere. Chapter 5 of the *Climate change projections* report gives details of the data available from the RCM ensemble, its advantages and limitations. Of course, users may wish to extend their analysis, and investigate the robustness of any adaptation decisions, using data from other global climate models. It is recommended that users do not revert to UKCIP02 scenarios in isolation, for any of the variables that are not available in UKCP09.

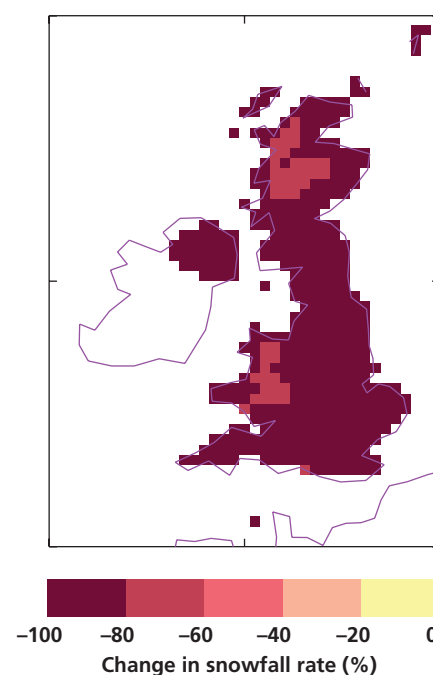


Figure 22: Percentage changes in mean wind speed in winter (left) and mean snowfall rate in winter (right), by the 2080s (relative to 1961–1990) under the Medium emissions scenario, averaged over the 11 members of the Met Office Hadley Centre RCM ensemble.

Projected changes in daily climate from the Weather Generator

The Weather Generator has been run for a control period corresponding to the UKCP09 baseline climate (1961–1990) and future time periods to estimate the changes in key climate indices at the daily level. Two types of analyses are presented here, for the differences between the baseline and future projection. Firstly, tables are presented of detailed measures for 4 sites across the UK. Secondly, maps of 25 km grids are presented showing patterns of changes.

There are different ways of sampling from a probabilistic distribution to develop Weather Generator output (see the User Guidance: <http://ukclimateprojections.defra.gov.uk>). The results shown below are Weather Generator outputs corresponding to change factors randomly sampled from the appropriate PDF for future climate under the Medium emissions scenario for the 2080s. Amongst the most notable changes related to temperature are increases in number of days with high temperatures nationwide and particularly in the south-east, along with reductions in frost days. Amongst changes related to rainfall are increases in dry spell frequency related to summer drying. Table 3 shows future and control percentiles of various temperature indices for 4 representative sites. The changes at 10, 50 and 90th percentile levels of a number of derived indices have been calculated. Major increases in numbers of hot days (above both 25 and 28°C) are found for the future projection.

Table 4 shows future and baseline percentiles of dry spell frequency for 4 representative sites. There are significant increases in the 10-day dry spell frequency associated with summer drying.

Table 3 (below): Three temperature indices calculated at four locations. Observed 1961–1990, simulated by the Weather Generator (WG) (1961–1990) and projected for the 2080s under the Medium emissions scenario. Results are given for 10, 50 and 90th percentiles, based on 100 runs of the Weather Generator to a random sample of the projections, averaging at the 50% probability level.

| | Observations | WG simulations 1961–1990 | | | WG projections 2080s Medium | | |
|---|--------------|-----------------------------|-----|-----|--------------------------------|-----|-----|
| | 50% | 10% | 50% | 90% | 10% | 50% | 90% |
| Annual number of days >28°C | | | | | | | |
| Heathrow (England) | 2 | 0 | 2 | 5 | 10 | 32 | 67 |
| Dale Fort (Wales) | 0 | 0 | 0 | 0 | 0 | 1 | 13 |
| Aldergrove (Northern Ireland) | 0 | 0 | 0 | 0 | 0 | 2 | 11 |
| Eskdalemuir (Scotland) | 0 | 0 | 0 | 0 | 0 | 3 | 12 |
| Annual number of days >25°C | | | | | | | |
| Heathrow | 15 | 7 | 12 | 19 | 36 | 70 | 104 |
| Dale Fort | 0 | 0 | 0 | 0 | 1 | 12 | 40 |
| Aldergrove | 0 | 0 | 0 | 2 | 3 | 13 | 34 |
| Eskdalemuir | 0 | 0 | 1 | 3 | 3 | 12 | 29 |
| Annual number of Frost days (minimum temperature ≤ 0°C) | | | | | | | |
| Heathrow | 39 | 27 | 37 | 51 | 2 | 9 | 23 |
| Dale Fort | 11 | 2 | 6 | 11 | 0 | 0 | 3 |
| Aldergrove | 44 | 35 | 43 | 56 | 3 | 11 | 26 |
| Eskdalemuir | 94 | 84 | 97 | 112 | 19 | 40 | 66 |

Ensembles of weather generator outputs were produced on a 25 km grid across the UK in a similar manner as for the sites. A sample of the outputs is shown here. Note that maps such as these are not available from the User Interface.

The largest increase in numbers of hot days is found in the south east of England (see Figure 24), where at the 50% probability level (central estimate) an increase from around 20 to more than 50 days per year is expected. The maps should be interpreted as showing the differences (increases) in frequency of hot days between the same percentile level. For example, the maps of change at 90th percentile level show the number of days per year which is exceeded on average in the top 10% of years. Finally, changes in the pattern of dry spells are shown in Figure 25, where modest increases are found across the country and substantial increases in the south and east associated with lower summer rainfall.

Table 4 (below): Frequency of dry spells greater than 10 days, at four locations. Observed 1961–1990, simulated by the Weather Generator (WG) (1961–1990) and projected for the 2080s under the Medium emissions scenario. Results are given for 10, 50 and 90th percentiles, based on 100 runs of the Weather Generator to a random sample of the projections, averaging at the 50% probability level.

| | Observations | WG simulations 1961–1990 | | | WG projections 2080s Medium | | |
|--|--------------|-----------------------------|-----|-----|--------------------------------|-----|-----|
| | 50% | 10% | 50% | 90% | 10% | 50% | 90% |
| Annual number of dry spells greater than 10 days | | | | | | | |
| Heathrow (England) | 9 | 5 | 8 | 11 | 7 | 11 | 15 |
| Dale Fort (Wales) | 7 | 3 | 5 | 8 | 4 | 7 | 10 |
| Aldergrove (Northern Ireland) | 5 | 1 | 3 | 5 | 2 | 5 | 8 |
| Eskdalemuir (Scotland) | 4 | 1 | 3 | 5 | 2 | 4 | 7 |

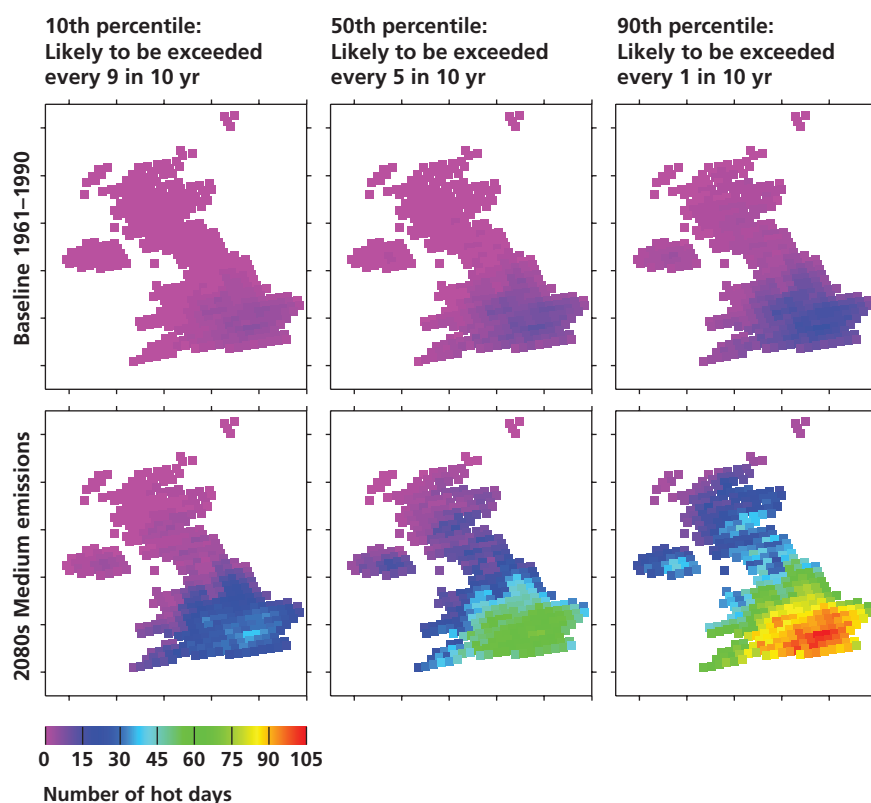


Figure 24: Numbers of hot days (above 25°C) annually estimated by the Weather Generator, for baseline (1961–1990) scenario (top row) and 2080s medium emissions scenario (bottom row).

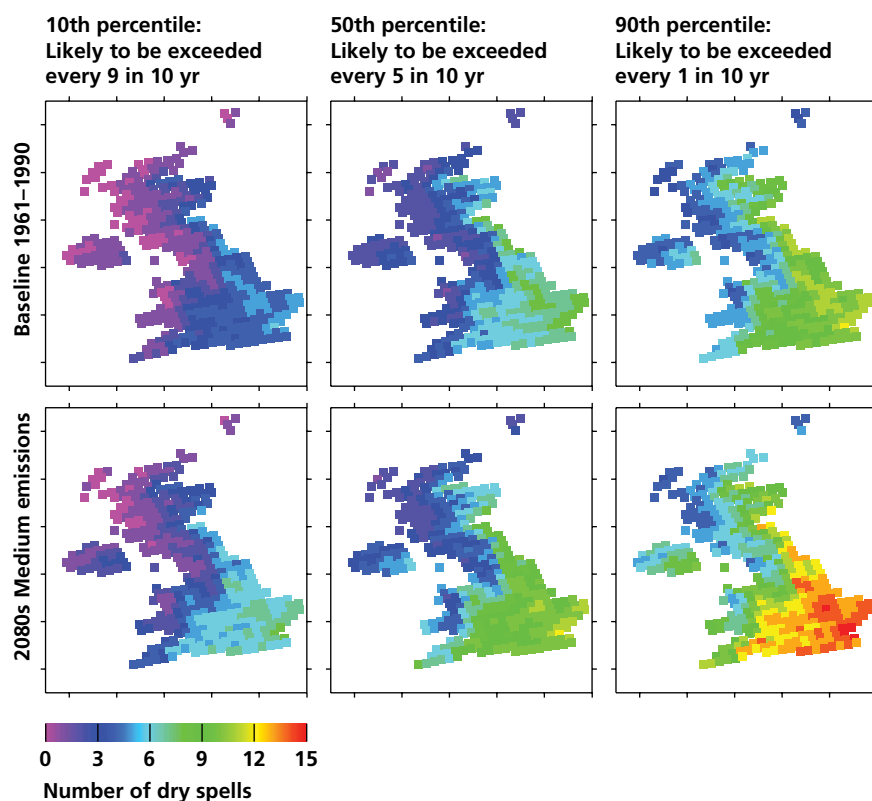


Figure 25: Numbers of dry spells longer than 10 days annually, estimated by the Weather Generator.

Will the Atlantic Ocean Circulation (*Gulf Stream*) change?

The North Atlantic Ocean Circulation (sometimes less precisely referred to as the *Gulf Stream*) maintains a warm North Atlantic, and as such is partly responsible for the climate of the UK being more temperate than other regions at the same latitude. If, hypothetically, the Atlantic Ocean Circulation were to be switched off the UK's climate would be a few degrees colder than today's. Climate models project that the Atlantic Ocean Circulation will weaken gradually in response to increasing greenhouse gases, by up to 50% by 2100, and the effect of such weakening is included in the UKCP09 Projections. However, no comprehensive climate model, when forced with the IPCC SRES emissions scenarios, produces a complete or abrupt shutdown in the 21st century. Although additional freshwater from rapid melting of the Greenland ice sheet could further weaken the Atlantic Ocean Circulation, IPCC AR4 concludes that it is very unlikely that an abrupt change will occur this century. We cannot comment with any confidence on changes that may have already happened, due to the lack of continuous, long term, robust, measurements.

How will climate in urban areas change?

Urban climates are different from those of surrounding rural areas, a phenomenon often known as the Urban Heat Island (UHI) effect. This arises partly because of the different terrain characteristics of city and countryside (such as their reflectivity and the friction effect of their surface), partly due to the ability of buildings to absorb heat by day and release it by night, and partly due to the energy dissipated within the city from human activities. Although the Met Office Hadley Centre regional climate model used in the UKCP09 projections does not include these factors, if they do not change significantly in the future, then it is

reasonable to add UKCP09 Projections of climate change to a baseline observed urban climate to get a future urban climate. In fact, the projections of future climate available from the User Interface partly include the current effects of urbanisation. But if there are changes in the amount of energy dissipated in cities (e.g. as air conditioning becomes more widespread), or if the structure of a city changes, or if climate change acts on cities differently to rural areas, these could change the UHI effect, and projecting future climates in cities will require additional techniques to be employed.

Limitations: shall we wait for improved projections?

The procedure used in UKCP09 to convert the ensembles of climate model simulations into probabilistic estimates of future climate necessitates a number of expert choices and assumptions, with the result that the probabilities we specify are themselves uncertain. We do know that our probabilistic estimates are robust to reasonable variations within these assumptions, and this is covered in some detail in Annex 2 of the UKCP09 report *Climate change projections*. Although it is important that prospective users understand the limitations and caveats, it is also worth emphasising that (a) current models are capable of simulating many aspects of global and regional climate with considerable skill; and (b) they do capture, albeit imperfectly, all the major physical and biogeochemical processes known to be likely to exert a significant influence on global and regional climate over the next 100 yr or so.

As our understanding of the climate system and our ability to represent it in models gets better, as statistical methods to convert model results into probabilistic projections are developed further, and as computing power increases, it is likely that uncertainties will become smaller, although natural variability will always provide an irreducible level in the long term. The consequence of these expected improvements is that the shape of a given PDF is likely to change in the future. Users need to understand clearly that, if they choose to adapt to a climate change corresponding to a specific probability level, this is likely to change in future projections — and the changes are likely to be greater at the extremes of probability levels (that is, 10 and 90%). If our understanding of climate processes, and model representations of them, does not change substantially in future, then we foresee a general reduction in uncertainties (except that due to long-term natural variability) because of improvements in our ability to represent processes currently modelled, and we would hence expect the shape of the PDF to change, with a reduction in its width. However, we do not know in what way this reduction in width will occur; in particular it may not be in a symmetrical manner. Although we cannot say what the next generation of PDFs will look like, it is likely that the spread of plausible changes they would indicate would be encompassed by the corresponding PDFs shown in UKCP09. Thus, in the absence of any major change in model projections, users who are incorporating the probabilities given in UKCP09 into their decision-making are likely to find that their decisions are robust to changes in the next generation of projections.

On the other hand, there is also the potential for uncertainties to become greater if processes not yet included, or included imperfectly, in the models turn out to exert a substantial influence on climate change. Less than decade ago, for example, carbon cycle feedbacks were not included in models, yet these are now known not only to change the projections substantially but also to add significantly to the uncertainty in them — which is why they are included in UKCP09. Further such effects, for example, methane feedbacks from land and oceans or the dynamics of ice sheets, may be shown to be important in due course. Uncertainties could

also widen if future (improved) models reveal that a process which is represented in the current generation of models, but with a common bias, turns out to exhibit a larger response to man-made forcing than current models suggest (see Box 4). However, the consistency between model simulations and observations of change over the last century provides some reassurance that any unknown processes are unlikely to change projections fundamentally, at least for the next few decades.

An obvious follow-up question is: should decisions be made now, based on UKCP09 Projections, or should they be delayed in the hope that better projections will be available in a few years time? How rapidly will climate projections change in future? Although modellers have improved many aspects of their models over the past decade or so, the current range of changes over the UK (Figure 4) is not significantly narrower than that shown in UKCIP02. In practice, the prospects for better projections will depend on which aspects of future climate users are most interested in. The width of the PDFs in UKCP09 are substantial even for the next few decades, due mainly to natural variability, and grow larger through the century due to uncertainties in climate feedbacks. It may be possible to reduce short-term uncertainties with higher resolution models which may simulate better (for example) the North Atlantic storm track, and by starting model experiments with the recently-observed state of the ocean. However, this may not improve projections of (say) changes in surface temperature a hundred years ahead; at these lead times improved projections would come from more faithful representations of climate feedbacks and the carbon cycle in models. Dialogue between decision makers and climate scientists, on the potential for emerging research to update projections, will be essential. We reiterate the key point made earlier that the UKCP09 methodology is designed to capture known uncertainties in the climate system built into the current generation of climate models, and is the most comprehensive approach to do so to date. The UKCP09 projections can make a useful contribution to assessing risks posed by future climate; they are appropriate for informing decisions on adaptation to long-term climate change which need to be taken on the basis of current knowledge, and the uncertainty quantified in them is likely to be a conservative estimate.

In the UKCP09 report *Climate change projections* and the online UKCP09 User Guidance, we discuss in depth the limitations of the projections and their sensitivity to some of the assumptions. Decision makers use projections of change in many factors; not just climate itself but also demography, economics, technologies, etc.; uncertainties in these are generally poorly quantified. The great strength of the UKCP09 projections is that they give decision makers the first quantification of the major known uncertainties in climate change over the UK; that these are large reflects the current situation in climate modelling.

Box 4: Comparison of the UKCP09 methodology for probabilistic projections with an alternative one

Would an entirely different methodology to the one developed for UKCP09 give different results? There is currently no independent approach which considers the full set of uncertainties covered in the UKCP09 methodology (i.e. large-scale effects of physical atmosphere and ocean processes, sulphur and carbon cycle feedbacks, combined with downscaling to regional scales). Also, there is no method which seeks to provide projections for the wide range of variables included in UKCP09, including consideration of joint changes for multiple combinations of these variables at different future periods. However, methods have been published which consider subsets of these types of uncertainty, applied to projections of key variables such as mean temperature and precipitation. A well-documented example is ASK (after authors Allen, Stott and Kettleborough) which projects future changes in surface temperature at global or sub-continental scales (e.g. northern Europe), with associated uncertainties, by assuming a linear relationship between errors in simulations of past and future climate changes. We applied the ASK technique to the simulations from 17 variants of the Met Office Hadley Centre global model, and derived the projections shown in Figure 26 (blue lines). We compared these with UKCP09 (red lines), omitting the sampling or carbon cycle and downscaling uncertainties from the UKCP09 projections, since these are not considered in ASK. The central estimate (50% probability level) of changes in temperature over northern Europe by the 2080s from the ASK method is about 4% higher than that using UKCP09, and gives a 25% narrower spread (10 to 90%). It is reassuring that two methods based on different principles and assumptions should give relatively similar projections in practice, when compared on a like-for-like basis. This further supports our own assessment that the UKCP09 Projections are likely to be relatively robust to the assumptions in the methodology used, and hence that the spread of outcomes is consistent with current evidence.

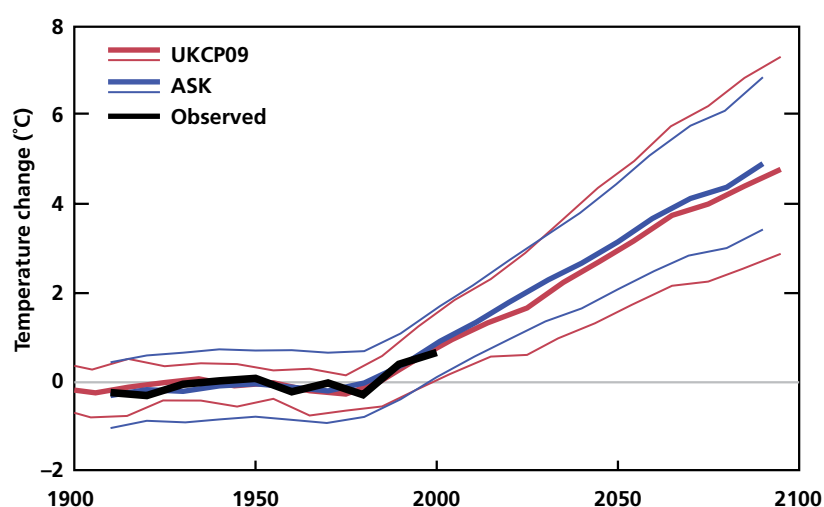


Figure 26: Comparison of probabilistic climate projections (10, 50 and 90% probability levels) for changes in 10-yr annual mean temperature under the UKCP09 Medium emissions scenario. Changes shown are for Northern Europe, relative to the average climate of 1906–2005. Results using the UKCP09 methodology are in red, those from the ASK method in blue. Observations are shown by the black line.

6 Marine and coastal projections

The maritime and coastal environments play an important role in the UK's culture and economy. Plausible estimates of how this environment will change in the future as the global climate adjusts to rising greenhouse gas concentrations are vital for adaptation planning.

The previous set of UK climate scenarios, UKCIP02, only contained limited information on sea level rise and a projection of changes in the extreme water levels based on a single climate model. In UKCP09 we provide a more diverse package of information comprising sea level rise and changes in: storm surges, water temperatures and salinity, shelf currents and offshore waves. The results cover both the coastline of the UK and the shelf seas (the area of relatively shallow sea around the UK). For sea level rise, storm surges and waves, the UKCP09 simulations provide a minimum estimate of uncertainty in projections of the future. It is not currently possible to produce probabilistic projections, such as those provided by UKCP09 for atmospheric changes.

An important feature of the new marine scenarios is their degree of consistency. This is created by using the same atmospheric climate model to provide inputs to the shelf sea models of storm surges, waves, temperature and salinity. This makes it possible, for the first time, to look at the joint occurrence of different types of marine and coastal change.

How were the marine scenarios constructed?

Climate simulations from 11 variants of the Met Office Hadley Centre global climate model, HadCM3, were used in the construction of the marine scenarios. Each model variant differed from the others in the way key climate processes were represented, but all of the versions were judged to provide credible representations of present-day climate. Global simulations were made for the period 1859–2100. They were downscaled to a regional resolution of 25 km for the period 1950–2100 using a regional climate model. Prior to 2000 the greenhouse gas concentrations followed historic observations. From 2000 they followed the Medium emissions scenario.

The storm surge simulations were made by using the winds and atmospheric pressure from the regional climate models to drive the 12 km scale Proudman Oceanographic Laboratory (POL) storm surge model for the period 1951–2100. Since 11 climate model versions were available this gave 11 different storm surge simulations, with the spread providing our estimate of uncertainty. The surge model itself was not varied.

For waves three climate model variants were selected, with high, low and mid-climate sensitivities. The downscaled winds from these three regional climate models were each used to drive a 12 km version of the wave models set up for the waters around the UK. Wave height and direction simulations were produced for two time-slices, 1961–1990 and 2070–2099.

For shelf hydrography a single climate model variant was selected from the three used in the wave simulations. The regional climate model variant provided winds, atmospheric pressure and fluxes of heat and moisture to drive the POLCOMS shelf seas model. Like the wave simulations, two 30-yr time periods were produced. Consistent changes in river run off were also applied from a river flow model, driven by the same regional climate model.

The production of sea level rise scenarios followed a different approach to the other marine variables. This is because the HadCM3 ensemble alone could not account for the spread expected in either global or regional sea level. The projected uncertainty range of global sea level is taken directly from the most recent Fourth Assessment Report of the IPCC, which was downscaled for the UK. An estimate of vertical land movements from a recent model study were added to absolute changes in order to provide the local relative change. Unlike the other marine projections, which are only provided for the Medium emissions scenario, sea level rise projections have also been made for the High and Low emissions scenarios.

The High++ scenario range of sea level rise and surge

Drawing on the methodology developed for the Environment Agency's Thames Estuary 2100 study, we also developed a High++ (extreme) scenario range for sea level rise and storm surges. This provides an additional amount of change above the likely range of current models.

For sea level the extra sea level rise in H++ primarily results from faster melting of ice sheets. Although we cannot yet predict how fast this will occur we can make estimates of its likely maximum size based on observations of the past, and plausible constraints on ice sheet dynamics.

The likely range of future surge trends only includes the effect of changes in storminess from the 11 Met Office Hadley Centre models. However, other international global climate models give a wider range of changes in the strength of storms over the UK than the Met Office Hadley Centre models. Our H++ surge simulation is based on a scaling method using the output from the climate model with the greatest UK increase in storm intensity in the future.

The H++ scenario range is intended to provide an extreme but physically plausible range of change for users wishing to investigate contingency planning and the limits of adaptation. However, it is thought very unlikely that the upper end of the H++ ranges for sea level rise and surge will be realised during the 21st century.

Key findings of the marine report

Sea level rise

Increases in greenhouse gases in the atmosphere are projected to lead to increased sea level, both through the heating and expansion of ocean water and through some melting of the world's ice sheets, ice caps and glaciers. The projection of sea levels increasing is very robust, with none of the models we considered projecting a net decrease in sea level, but the size of the rise is still uncertain.

Sea level rise for a particular region generally differs from the global mean. This is because local sea level is affected by ocean circulation and by geographical variations in the temperature and/or salinity of the water column. The range of absolute sea level rise around the UK (before land movements are included) and across the three emissions scenarios is projected to be between 12 and 76 cm for the period 1990–2095, which is a wider spread than that of the global average. The contribution to the uncertainty from the modelling was found to be larger than the uncertainty in emissions scenario, which is expected because of the long response time associated with sea level changes. The low probability, High++ sea level range, is based on observations of the past and plausible constraints on ice sheet dynamics. This comprises an absolute sea level rise estimate for the UK of 93 cm to 1.9 m by 2100.

The vertical movement of the land varies around the UK coastline. Taking this into account gives slightly larger sea level rise projections relative to the land in the more southern parts of the UK where land is subsiding, and somewhat lower increases in relative sea level for the north. The relative sea level rise at 4 sample locations are shown in Figure 27.

Projected changes in storm surges

By comparison with observations of 50-yr return levels (surge levels which tend to occur once every 50 yr on average) we found that the UKCP09 modelling system for storm surge is generally better at simulating present day surges than that used in UKCIP02. The much longer time-slices used in UKCP09 for storm surge simulations, 150 yr instead of two sets of 30 yr, enabled better characterisation of long periods of natural variability.

Future changes in storm surges are characterised using a measure called the skew surge. This is the difference between the elevation of the projected astronomical high tide and the nearest (in time) simulated high water, shown in Figure 28.

The projected long-term future trends in storm surge that we find in UKCP09 are physically small everywhere around the UK, and in many places can be accounted for by natural variability. The surge level we expect to be exceeded on average once in 2, 10, 20 or 50 yr is not projected to increase by more than 9 cm by 2100 anywhere around the UK coast (not including the mean sea level change). The largest trends are found in the Bristol Channel and Severn Estuary. A map of 50-yr return period changes is shown in Figure 29.

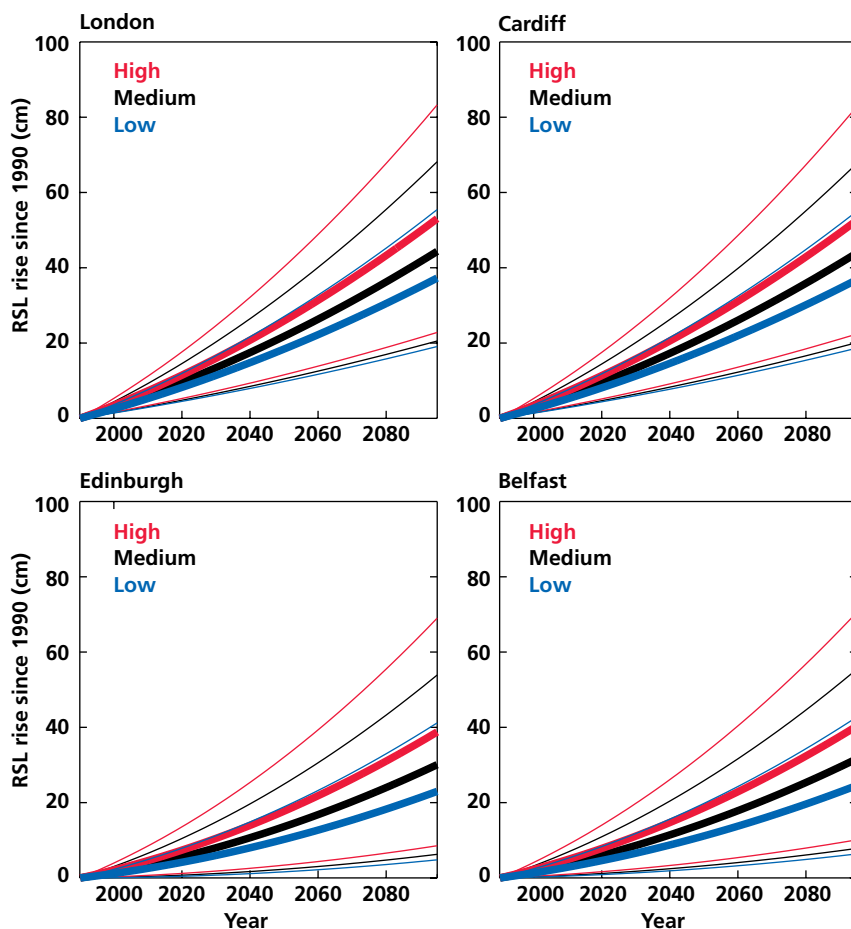


Figure 27: Relative sea level (RSL) rise over the 21st century showing central estimate values (thick lines) and 5th and 95th percentile limits of the range of uncertainty (thin lines) for four sample locations around the UK and the three emissions scenarios. Values are relative to 1990.

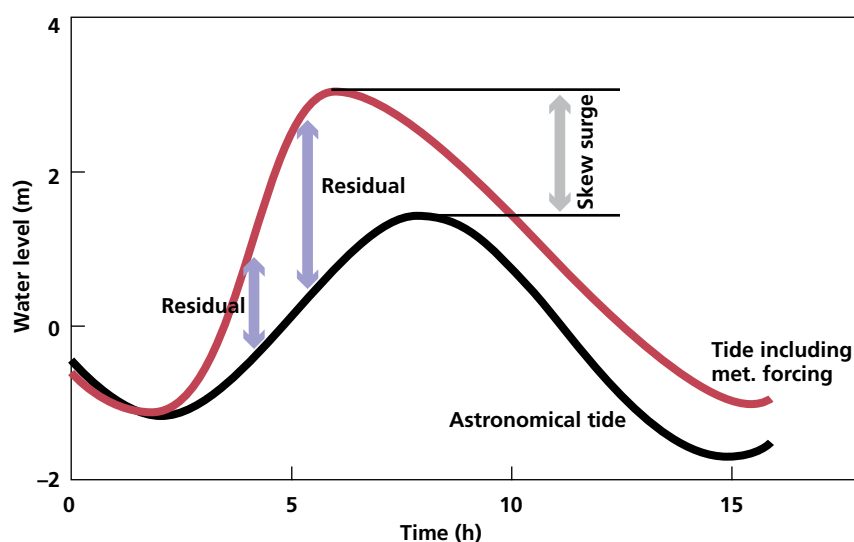


Figure 28: Schematic diagram showing how skew surge and surge residual are evaluated. The surge residual changes through the tidal cycle, usually peaking before either the astronomical or the met-forced tide. The skew surge is evaluated just once and is a more useful measure.

Combined changes in storm surges and relative local sea level rise can be estimated approximately by simply adding together the two components. The error introduced by doing this on extreme water level changes was found to be small for the range of surge changes and sea level rise simulated in UKCP09.

For the H++ surge projections, the inferred increases in the 50-yr return level surge are physically large in places around the UK, reaching up to almost 95 cm in the Thames region.

When this is combined with the H++ sea level rise component the combined extreme water level scenario has increases over the 21st century of up to 3 m for the 50-yr return period event.

Projected changes in offshore waves

Like the other modelling systems used to produce marine climate projection this report, the wave model, when connected to the Met Office Hadley Centre climate models, was found to have some skill at simulating observed wave conditions of the present day.

The simulations show that in the future, seasonal mean and extreme waves are generally expected to increase to the South West of the UK, reduce to the north of the UK and experience a small change in the southern North Sea. Changes in the winter mean wave height are projected to be between –35 and +5 cm. Changes in the annual maxima are projected to be between –1.5 and +1 m (Figure 30).

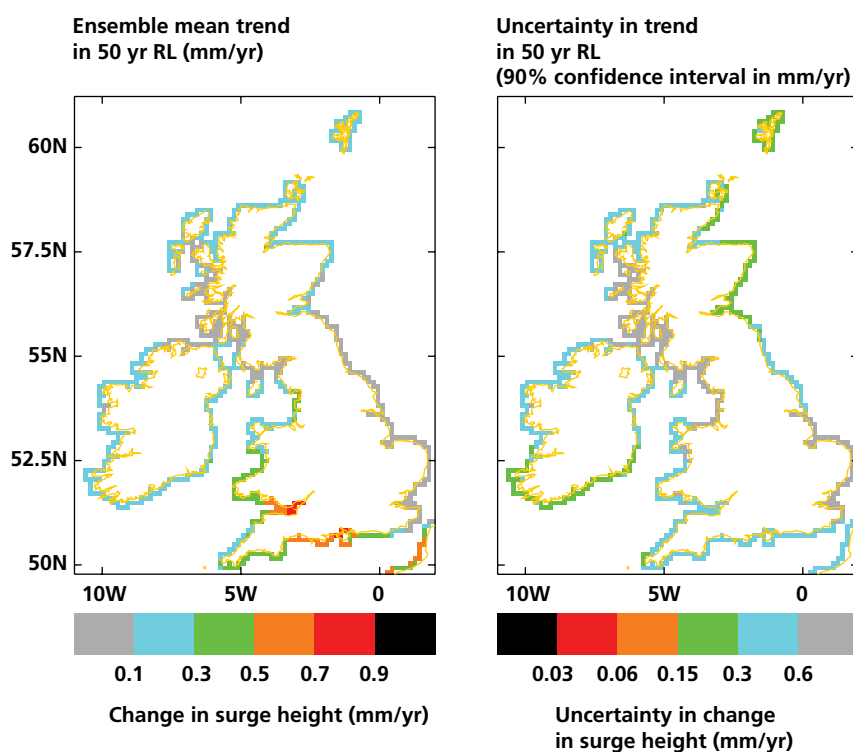


Figure 29: Ensemble mean trends (and uncertainty range) in 50-yr skew surge return level from the storminess component only. Negative trends are included in the grey shading.

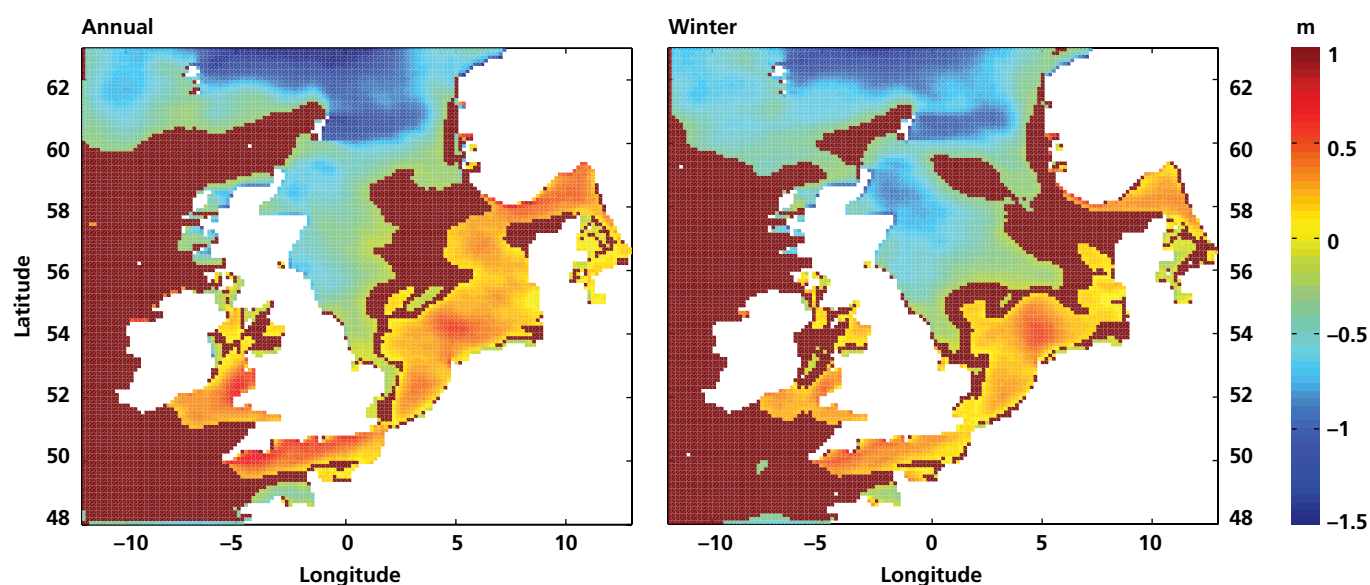
Currently, there are large uncertainties associated with projected changes in waves, especially with the variations in extreme values. Projections of more extreme (longer return period) wave heights reflect the same pattern as the mean changes but with increased uncertainty. No H++ scenario has yet been developed for waves.

Projected changes in sub-surface ocean variables

As the techniques employed to model subsurface changes are new, no attempt has yet been made to incorporate uncertainty in the future projections of shelf sea temperature, salinity and circulation. Instead the scenarios provide a physically plausible illustration of one future that might be realised under the UKCP09 medium emissions scenario. In order to better quantify these general trends, simulations that account for the oceanic influence of the North Atlantic more accurately will be required. To better understand the uncertainty in these trends will require simulations based on an ensemble of scenarios. Despite these limitations, the modelling system was shown to have some skill at simulating present-day shelf sea conditions, as a test of its robustness.

The simulations indicate that the shallow shelf seas around the UK are likely to experience the effects of climate change over the next century in a different way to the deep ocean. The shelf seas around the UK are projected to be 1.5–4°C warmer (Figure 31) and ~0.2 practical salinity units (p.s.u.) fresher (lower salinity) by the end of the 21st century for a medium emissions scenario. The stratification of the shelf seas into deeper more saline water and overlying fresher water continues to occur every summer but the strength of this stratification is projected to increase in future. The period of stratification is also projected to become longer, starting around 5 days earlier and breaking down 5–10 days later each year.

Figure 30: Changes in mean annual and winter maxima of significant wave height from 1960–1990 to 2070–2100. Left panel is mean annual maxima and right panel is mean winter (DJF) maxima. Areas that are masked out (dark red) are points where the differences are statistically insignificant at the 95th percentile level.

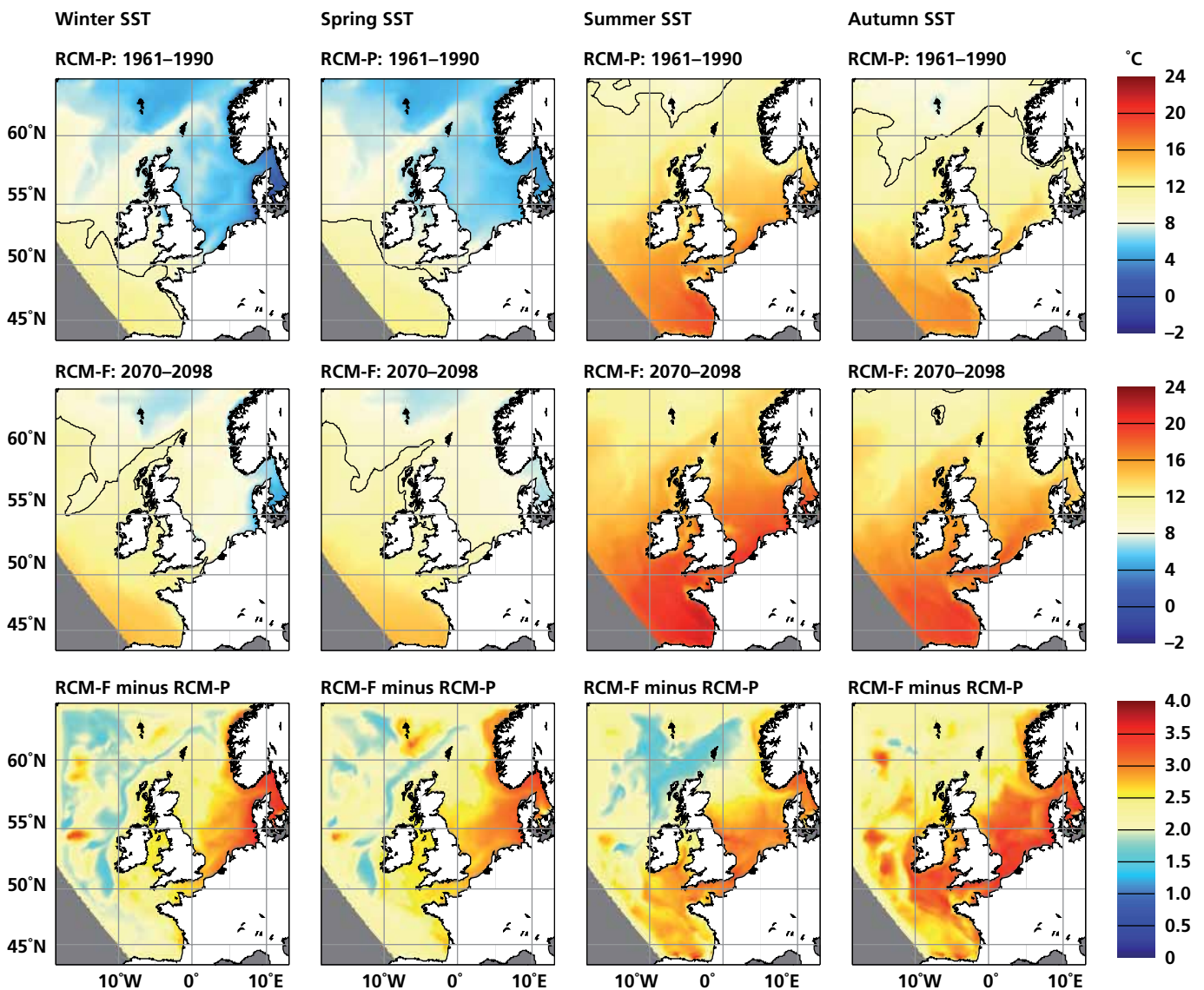


Limitations of the UKCP09 marine projections

The marine projections in UKCP09 are an improvement on previous work. However, climate science cannot yet provide a complete picture of future changes to the maritime environment. When using them it is vital that their limitations are understood and kept in mind. Some of the key limitations are listed below:

- Global model.** The quality of the marine simulations is dependent on the quality of the simulations produced by the underlying global climate models. Such models are in a process of continuing development with new physical, chemical and biological processes being incorporated on an ongoing basis. For example, recent studies have highlighted the importance of the carbon cycle (not explicitly simulated in the marine scenarios) in contributing to the uncertainties in temperature change, and the importance of stratospheric processes (currently not well simulated) in determining century-scale movements in the storm tracks. Thus the likely uncertainty ranges based on global climate models in the marine report should be considered minimum uncertainty ranges.

Figure 31: Seasonal mean sea surface temperature (SST) for RCM-P (1961–1990) and RCM-F (2070–2098) and the differences between them.



- **Emission scenario.** For most variables, only the Medium emissions scenario has been used. For sea level the High and Low scenarios have been incorporated but none of the emissions scenarios include any explicit mitigation policy. Surges, waves and shelf sea hydrography were not scaled to High and Low emission scenarios because there was no clear indication what the choice of scaling variable should be from earlier work. Furthermore, there were insufficient results available to us in this study to test any speculative scaling for these variables.
- **Time period.** Trends in wave and sub-surface hydrology have been assessed using 30-yr time periods, which prior to UKCP09 has been a standard technique. However the UKCP09 surge research, and other recent work, has suggested that the variability in extremes diagnosed from such time periods is large, and that a diagnosis of trends using the whole of a century-scale simulation is more robust.
- **Shelf sea and wave model parameters.** Although for storm surge the range of uncertainty is dominated by that of the driving atmospheric conditions, in the POLCOMS model used to study shelf hydrography there are a large number of parameters, some of which are also quite uncertain. Therefore in the future, an estimate of shelf hydrography uncertainty will need to include both uncertainty in driving atmospheric conditions and uncertainty in the shelf sea model. This limitation also applies to characterising uncertainty in wave height and direction.
- **Ice processes** represent a major source of uncertainty in mean sea level change and account for the difference between the ensemble projection and the top of the H++ range. Ice dynamics are not well-represented (nor even well-understood) in the current generation of climate models and whilst the H++ range represents expert judgement based on observational evidence, it is not yet possible to estimate the likelihood of large changes in sea level, nor to construct a credible model of all the relevant ice processes on a global scale.

Acronyms

| | |
|-------|---|
| AR4 | Fourth Assessment Report (2007) from IPCC |
| ASK | Allen, Stott and Kettleborough |
| BADC | British Atmospheric Data Centre |
| CDF | Cumulative Distribution Function |
| CET | Central England Temperature |
| GCM | Global Climate Model |
| IPCC | Intergovernmental Panel on Climate Change |
| PDF | Probability Density Function |
| RCM | Regional Climate Model |
| SRES | Special Report on Emissions Scenarios |
| UHI | Urban Heat Island |
| UKCIP | UK Climate Impacts Programme |

Department for Environment, Food and Rural Affairs (Defra)

www.defra.gov.uk

Contact: helpline@defra.gsi.gov.uk

The Department for Environment, Food and Rural Affairs' core purpose is to improve the current and future quality of life. The Department brings together the interests of the environment and the rural economy; farmers and the countryside; the food we eat, the air we breathe and the water we drink. Defra's first Departmental Strategic Objective is "A society that is adapting to the effects of climate change, through a national programme of action and a contribution to international action". To help us meet this goal, Defra has funded the UK Climate Projections programme on behalf of the UK Government and Devolved Administrations to provide updated climate information for the UK from 1961–2099.

Department of Energy and Climate Change

www.decc.gov.uk

Contact: enquiries@decc.gsi.gov.uk

The Department of Energy and Climate Change brings together activities on climate change and energy policy and science from across Government. One of DECC's key objectives is to lead the global effort avoid dangerous climate change. To achieve this objective, it funds underpinning climate science and modelling work in the UK to provide the evidence necessary for Government to form robust policies on climate change mitigation and adaptation. The Department is the largest contributor to the Met Office Hadley Centre Integrated Climate Programme, which includes the modelling work for the UK Climate Projections.

Met Office Hadley Centre

www.metoffice.gov.uk/research/hadleycentre Contact: enquiries@metoffice.gov.uk

The Met Office Hadley Centre is the UK government centre for research into the science of climate change and its impacts. It was opened in 1990, building on the previous 20 years of research into climate change. Its Integrated Climate Change Programme is funded jointly by the Department of Energy and Climate Change (DECC), the Department for Environment, Food and Rural Affairs (Defra) and the Ministry of Defence (MoD). Its main roles are to:

- Improve our understanding of climate and use this to develop better climate models.
- Monitor climate variability and change at global and national scales, and use models to attribute recent changes to specific factors such as human activity.
- Quantify and reduce uncertainty in projections of climate change, particularly at a local scale and of extremes, and use this information to inform adaptation strategies.
- Define and assess the risk of dangerous climate change, whether gradual, abrupt or irreversible.
- Assess scientific aspects of options for mitigating climate change and its impacts.
- To advise government, business, the media and other stakeholders.

UK Climate Impacts Programme

www.ukcip.org.uk

Contact: enquiries@ukcip.org.uk

The UK Climate Impacts Programme works at the boundary between research and society on the impacts of climate change and on adapting to those impacts. UKCIP works by promoting stakeholder-led research, and by developing tools and datasets to help organisations adapt to unavoidable climate change. UKCIP supports the users of UKCIP02 and UK Climate Projections.

UKCIP was established in 1997, and based at the School of Geography and the Environment, Oxford. Defra funds UKCIP for the UK Government, Scottish Government, the Welsh Assembly Government and Department of the Environment Northern Ireland.

UK Climate Projections
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UK Climate
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